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# Bonded joint strength versus loading rate

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# BONDED JOINT STRENGTH VERSUS LOADING RATE

BY

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THESIS

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Approved by

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R. F. Davidson Ralph E. Schowalter

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The author wishes to thank Mr. G. R. Baumgartner for his constant assistance while conducting the tests.

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## INTRODUCTION

The purpose of this investigation was to determine the influence of the rate of loading variable on the apparent shear strengths of joints bonded with some of the currently available metal-to-metal adhesives. The effects of this variable are sometimes neglected by testing laboratories. The results of an experimental evaluation of the mechanical behavior of a group on modern metal-to-metal adhesives as a function of the rate of load application are used to more accurately establish the importance of rate of load considerations in adhesive joint testing. An attempt is made to explain observations of other investigators engaged in adhesive joint testing in terms of information gained from these experiments. The author has been unable to find published evidence of previous experimentation in this specific area of adhesive joint testing.

A series of tests was conducted by H. W. Eickner to determine the shear, fatigue, bend, impact and long-time-load strength properties of structural metal-to-metal adhesives. (1) These tests were sponsored by the Air Force-Navy-Civil Subcommittee on Aircraft Design Criteria. While discussing a particular standard shear test, Mr. Eickner makes the following observation: "It is known that faster rates of loading will give somewhat higher failing loads in this test*, and some of the high shear values reported by other laboratories for some of these same adhesives were obtained when faster rates of loading were used than prescribed in the specification. It would seem that a rate of 600 to 700 pounds per minute on the 1/2-square-inch

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(1) All references are in bibliography.

* The test referred to is a lap-joint shear test.

specimen would be reasonable, but some further tests should be made to determine the relationship between results with the two rates of loading."

U. F. Hribar of the Technical Staff of Hughes Aircraft Company reports the following observation: "Load rates for specimens tested under radiant heating conditions were four times as rapid as for hot dry air (approaching 5,000 psi per minute). Load rates up to 1,000,000 psi per minute have been found to have no appreciable effect on the tensile shear properties of high modulus* adhesives." (2)

A test was designed to isolate the rate of loading variable and to measure its effects on the shear strength of some commercial adhesives. The results of this test are used to offer an explanation of the rate of loading effects observed in standard adhesive tests.

Some of the limitations of the present testing methods are also discussed. A brief review of the history of the use of adhesives is included to further establish the place of structural adhesives in present day technology and to illustrate the need for more complete and accurate testing methods.

* The word "modulus" as used in this thesis refers to the "elastic modulus".

HISTORY

The use of adhesives started with the first developments of human ingenuity. Prehistoric tribes used resins to repair broken pottery and to help fix sharp objects to handles for use as tools and weapons. Statues were found in excavated Babylonian temples which had their ivory eyeballs fixed by bituminous cements 6,000 years ago. Adhesives made from egg white and lime were used by the Goths in decorating small wooden boxes with Roman coins 2,000 years ago. Today the coins still stick firmly to little pieces of rotted wood.

The Romans and Greeks used adhesives to veneer and as protective coatings for paintings. Many well preserved murals have been recovered from the ruins of Pompeii. (3)

Adhesive technology remained stagnent through the medieval period. During the Renaissance, however, many new adhesives were developed using trial and error methods of formulation. In earlier years, most technical papers on adhesives dealt largely with the tabulation of various recipes. Today it is possible to predict some of the physical nature of the materials.

The first glue factory in the United States was established in 1808. (4) Early glues were made out of aqueous extracts from the bones and skins of animals and fish. These extracts, when dried, and later dissolved in hot water provided a fairly good adhesive. The major industrial use of the early glues was the manufacture of furniture and books.

The terms "adhesive" and "glue" were often considered synonymous because the early adhesives were glues. During the early part of the twentieth century many new adhesives were compounded using natural and synthetic resins. The term adhesive is the more inclusive expression for a substance used to promote a bond between two or more substances while the word "glue" is reserved for adhesives of animal origin.

The synthetic resin adhesives maintained their strength under severe temperature and humidity changes - conditions extremely detremental to the earlier animal adhesives. These qualities inspired confidence among engineers and designers. Resin adhesives were accepted for use in applications requiring high strength and permanence. The large scale application of laminated wood to boat, aircraft and building construction during World War II provides an example of the general acceptance of the adhesive as a reliable structural material. Synthetic resin adhesives for corrugated paper-board manufacture and pressure sensitive tapes are more recent.

In the last decade the aircraft industries have made broad use of synthetic resin adhesives for bonding metal-to-metal. Today adhesives are used extensively on helicopters, missiles, and other types of aircraft, not only in secondary structural applications, but also in primary structural components.

## INTRODUCTION TO DISCUSSION OF STANDARD TESTS

The Convair B-58 bomber uses adhesive bonded structure for approximately 95% of the aircraft surface. This bomber is capable of sustained supersonic flight. In this region of aircraft operation, the structure is highly stressed and is subjected to severe temperature conditions.

The wide use of metal-to-metal adhesives for such critical applications creates a need for accurate and representative tests for determining the more basic strength properties of the adhesive. Included in these properties are the cohesive strength of the adhesive under shear loads, the cohesive strength of the adhesive under tensile loads, the modulus of the material under each of these, and variation of these properties with variations in rate of load application. (5)

At the present time, the standard tests used for determining adhesive joint strengths provide information that is difficult to apply to situations and configurations that differ significantly from the test situation and configuration.

Due to the absence of basic knowledge of the individual properties of adhesive materials it is difficult to accurately predict the performance of a joint acting as a part of a complete bonded assembly. Consequently, it is necessary to test the final bonded assembly in order to determine its overall acceptability. The final design must, therefore, be approached by using trial and error techniques. It is usually necessary to test the assembly to destruction. This design practice can become very expensive if many assemblies must be tested before the final design is established.

A non-destructive test of adhesive joints using ultra-sonic waves is sometimes used in the aircraft industry. With this method, it is possible to detect unbonded areas which reduce the strength of the assembly. A production assembly may also be compared to a standard assembly using an ultra-sonic inspection instrument. This method is used by Convair in the production of the B-58. (6) Dietz has used ultra-sonic waves to measure the dynamic moduli of adhesive joints in an attempt to predict joint strength. (7) (8) The ultra-sonic inspection techniques give good answers in some specific cases, but need to be further refined to be of general use in industry.

VARIABLES IN ADHESIVE JOINT TESTING

A general discussion of some of the variables entering the scene of adhesive joint testing is included at this time for the purpose of making subsequent discussions of standard adhesive joint test methods more meaningful. A discussion of the individual variables that apply specifically to this test and an explanation of how they were eliminated or controlled is presented in more detail in the discussion of the test apparatus and preparation of specimens.

The variables encountered in adhesive joint testing may be arranged into three general groups:

(a) Chemical changes of the adhesive material

(b) Adhesive application and cure technique

(c) Testing geometry and environment

For a given commercial adhesive material, heat treatment, ageing, contamination and proper mixing of multi-component adhesives could be listed as chemical considerations. These variables may be controlled by the following of the manufacturers recommendations for storing and mixing the adhesive.

Variables of application and cure technique would include: curing temperature, curing time, surface treatment, surface cleaning procedure, glue line thickness, adhesive film continuity and edge geometry of the joint. Curing procedure and surface preparation are specified by the manufacturer of the adhesive. The person testing the adhesive is responsible for maintaining constant joint geometry.

Testing geometry and environment should comply to some controlled standard set of conditions. Variables to be controlled at this stage of the test are: Test temperature, test humidity, testing machine jaw alignment and rate of load application.

In this investigation, an attempt is made to experimentally separate the effect of this last variable, rate of load application, upon apparent joint strength.

## ASTM STANDARD TESTS

The publication, "ASTM Standards on Adhesives", brought together all the ASTM methods of test pertaining to adhesives. Included are descriptions of standard shear and tension tests for metal-to-metal adhesives. The standard shear strength tests are of special interest in this investigation.

### ASTM-D905-49 STRENGTH PROPERTIES OF ADHESIVES IN SHEAR BY COMPRESSION LOADING

In this test, two blocks are bonded together as shown in Figure 1 with the adhesive under test. These blocks are then placed in a testing jig and loaded with a compressive force in a testing machine.

When testing high strength adhesives, small misalignments and deformations of the loading jig and the shear blocks can cause a considerable moment to appear in the specimen, complicating the stress situation in the joint. Figure 1 illustrates this moment. Differential straining of the test blocks results in stress concentrations at the edges of the glue line. (The effects of differential straining will be discussed in more detail in the next topic.) In view of these weaknesses, the shear block test should not be expected to reveal the true shear strength of the adhesive.

During the summer of 1957 while employed at the Naval Ordnance Test Station, the author conducted a series of tests on a particular

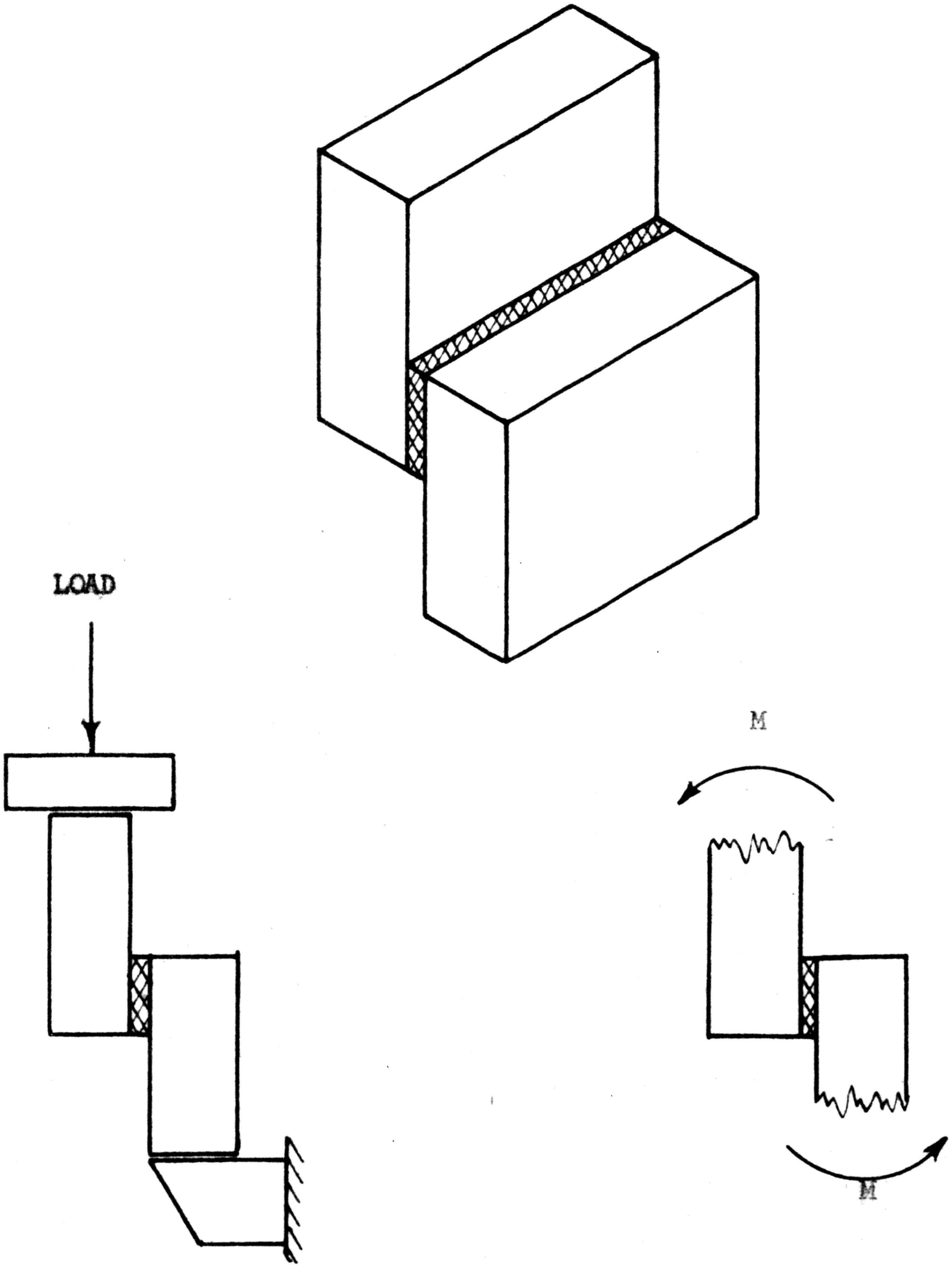



Figure 1  Shear block specimen

metal-to-metal adhesive using a compressive, shear-block technique. Considerable difficulty was experienced in obtaining reproducible data from this test. (9) The variable effects of the overturning moment were blamed for this lack of control.

The maximum rate of loading for this test is specified as 0.015 inches per minute loading head velocity with a permissible variation of plus or minus twenty-five percent.

ASTM-D1002-53T STRENGTH PROPERTIES OF ADHESIVES IN SHEAR BY TENSION LOADING

In this test, two sheets, 0.064 inches in thickness, are overlapped and bonded together. (See Figure 2.) The width of the specimen is one inch and the amount of overlap is determined from the estimated strength of the adhesive being tested. When testing some of the high strength adhesives, the metal sheet may fail in tension before the adhesive fails if the length of overlap is too great. The lap joint test is often used in industry for evaluating adhesive strengths because of its simplicity.

Adhesives are evaluated in this test by comparing their mean stress, defined as the load divided by the bonded area. The stress, however, is not uniform along the lap joint and the peak stress may be several times higher than the apparent or mean stress. The peak stress developed in a lap joint is dependent on the geometrical proportions and the elastic constants of the materials of the joint.

When testing high strength adhesives the stresses rising from the differential straining of the joined members becomes significant. The effects of differential straining are illustrated in Figure 3. The thickness of the adhesive layer is exaggerated for purposes of

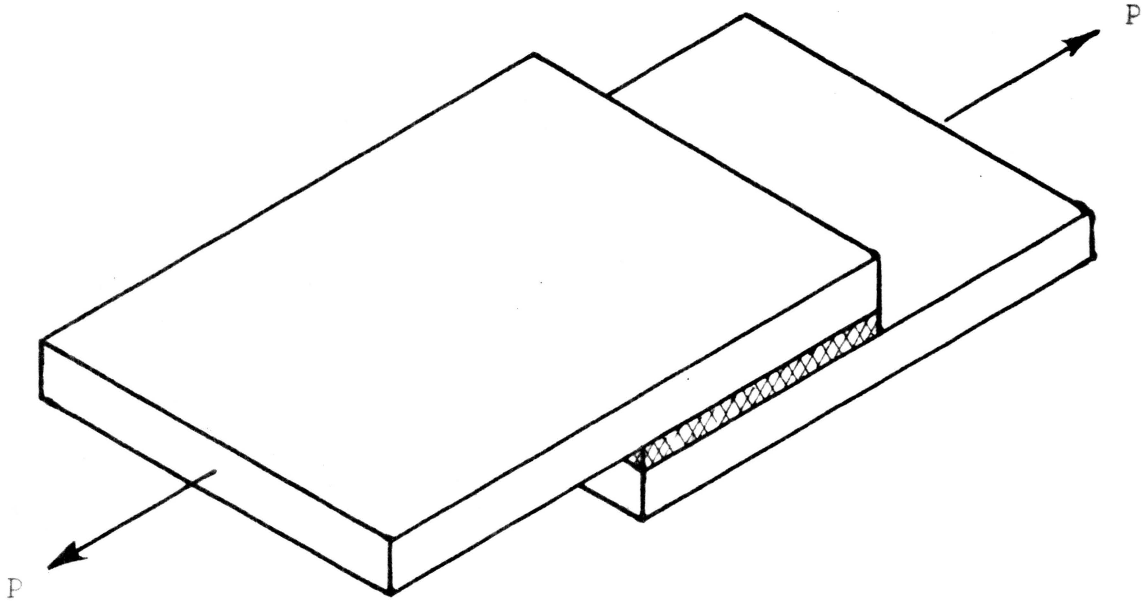
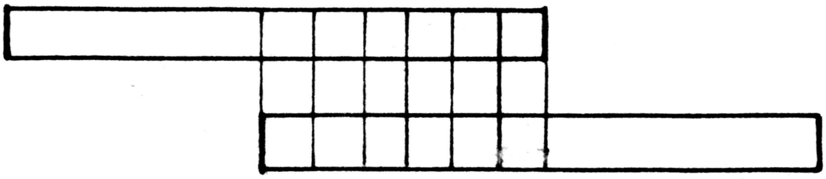



Figure 2  Lap Joint specimen

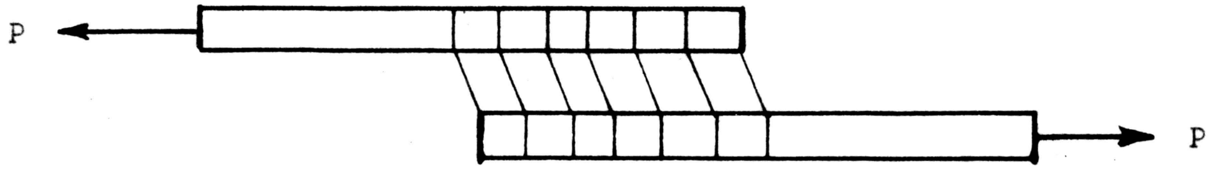
demonstration. Figure 3(a) shows a lap joint with rigid adherends. Note that the adhesive layer is uniformly deformed along the joint. Figure 3(b) shows a loaded lap joint with elastic adherends. If these adherends are extensible and obey the laws of elasticity, these members will develop strains proportional to the existing stresses. The adhesive at the edges of the lap joint will consequently be strained more than the adhesive at the center of the joint. This has been proved by various tests which demonstrate that the failure starts at the edge of the joint. (10)

The above are also confirmed by the higher strengths of joints with tapered members; Figure 3, in which the differential strain and the resulting stress concentrations at the edges are considerably reduced. The cross section of each member diminishes as the load borne by each member thus producing almost constant stress throughout the overlap and resulting in equal and smaller displacements. (11) Tapered or scarf joints are not often used in industrial practice because of the extra time required to machine the tapered ends.

If the adherends are elastic, an axial load applied to the specimen will give rise to a moment at the joint. (See Figure 4.) This moment tends to deform the specimen into the distorted configuration shown in Figure 4(b). This distortion produces tearing or tensile stresses in the joint. Several analyses of the stress situation existing within the adhesive layer of a lap joint specimen have been made. Considered in these analyses are the effects of joint geometry, adhesive and adherend elastic constants, the effects of differential straining and the bending moment in the joint. (12) (13) (14) The maximum shear stress at the edges is found to be approximately

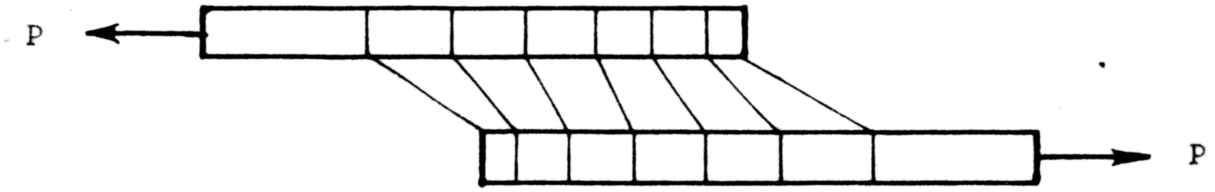


Unloaded lap joint



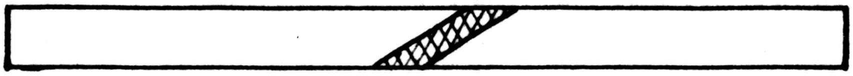

Loaded joint with rigid adherends

(a)




Loaded joint with elastic adherends

(b)



Scarf joint

(c)

Figure 3 Schematic diagram illustrating the effects of differential straining of a lap joint specimen

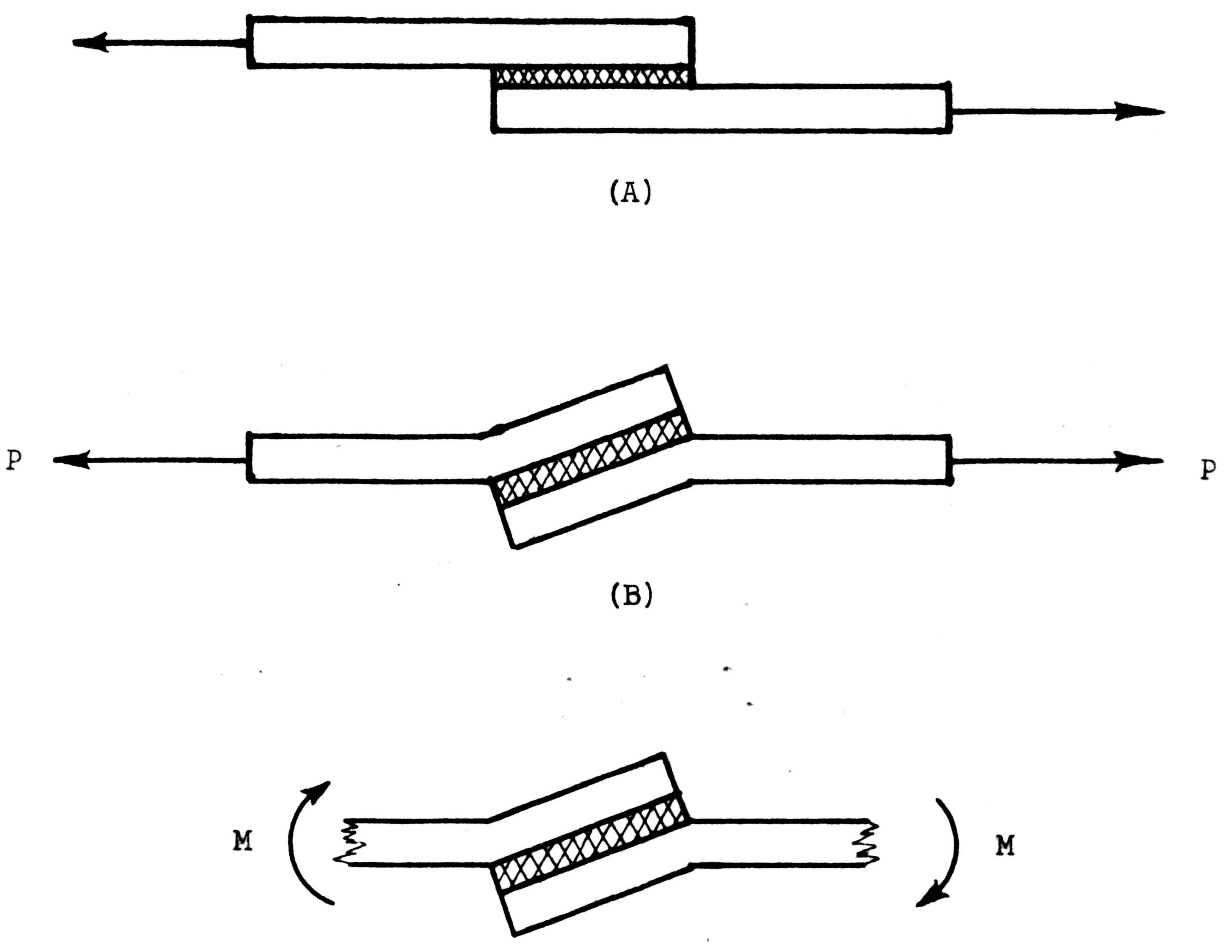



Figure 4 Schematic diagram illustrating the bending of the adherends of a lap joint as the joint is loaded

five times the mean shear stress in the joint. The stress distribution along a lap joint is shown in Figure 5. The curve showing the stress distribution by the theory of Goland and Reissner is shown along with an experimental determination. (15)

The results of lap joint tests are very useful if one is concerned with the design of lap joints. The test, however, provides little information as to the individual shear and tensile strengths of the adhesive material which must be known in order to design an adhesive joint. The lap joint is very sensitive to stress concentrations located on the highly stressed edges of the joint. Considerable difficulty is experienced in obtaining reproducible data from this experiment. In order to successfully separate a relatively small variable such as the effects of variable loading rate, using the lap joint test specimens, it becomes necessary to run a very large number of tests and to analyze the data statistically. The adhesive in the joint is not uniformly stressed, therefore, a stress-strain curve taken from a lap joint would not reveal the true stress-strain relationship for the adhesive material, since the stress-strain relationship for the adhesive is needed to explain the rate of loading variable, a more simple and direct test was used for the investigation. The rate of loading for the lap joint test is specified as either 200-700 pounds per minute or a loading head speed of .05 inches per minute.

## THE TORSION-SHEAR JOINT

If two thin walled cylinders are bonded end to end and the assembly loaded in torsion, the resulting stress in the bonded joint will be pure shear. A schematic diagram of a mechanism that could

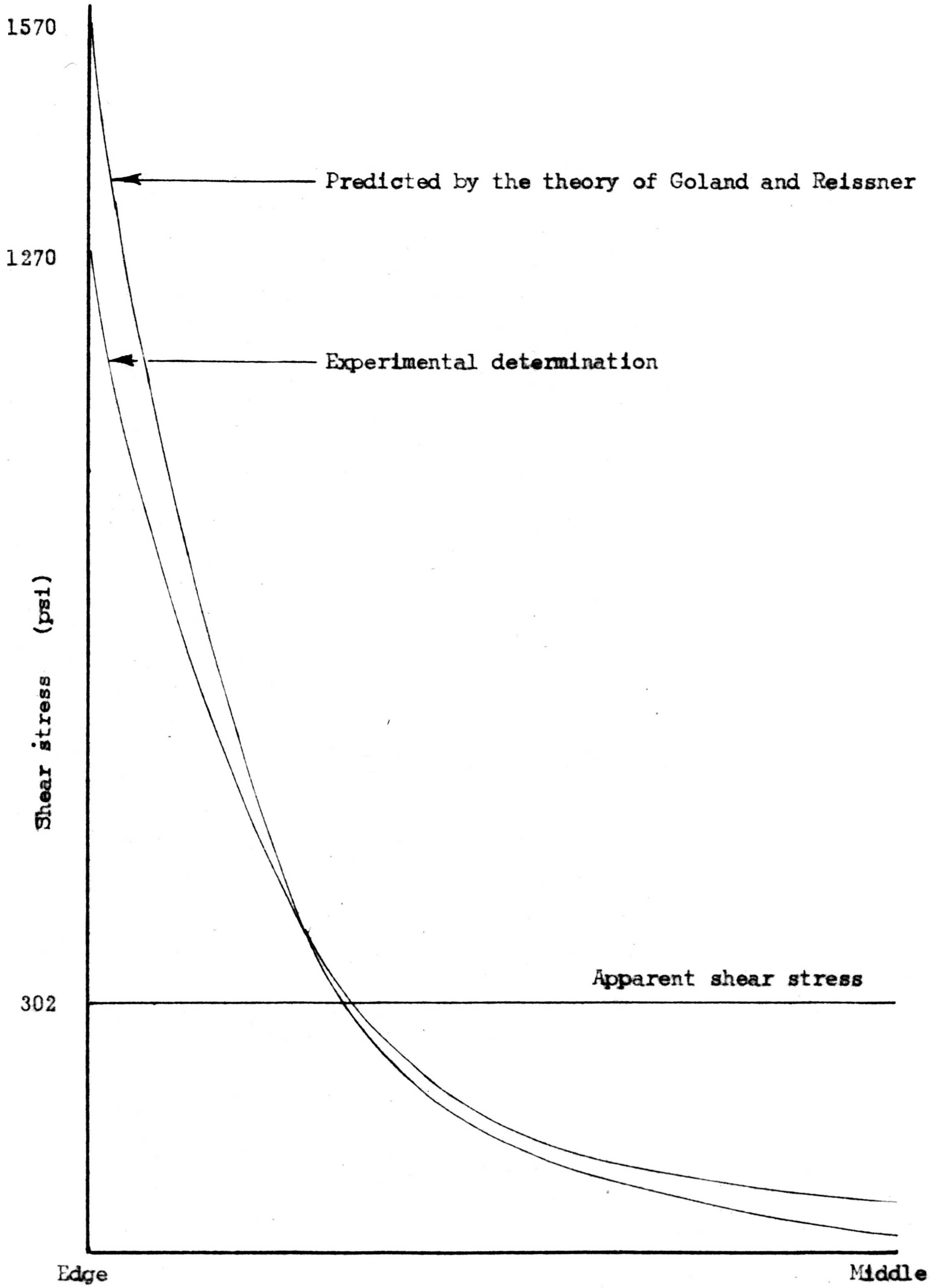



Figure 5 Typical stress distribution in a lap joint specimen

accomplish this type of loading is shown in Figure 6. Note that as the cylinders are loaded, the thickness of the wall does not change, or in other words, the radial strain is zero; therefore, in this type of joint, there will be no radial stress due to differential radial strain. If the cylinders are perfectly aligned and the axial friction is reduced to zero, the axial load and the longitudinal bending moment are zero. The joint is subjected only to pure shear due to the pure torsion in the thin walled cylinders.

A better value of the true shear strength of an adhesive may be determined by using the torsion test because of the simplicity of the stress situation in the joint. The Division of Mechanical Engineers of the National Research Council (Canada) has successfully built and tested such a torsion machine for applying pure shear stress to an adhesive joint. (16) A torsion-shear apparatus was designed and built by the author for use in variable rate of loading tests reported in this paper.

The average shear stress may be calculated by dividing the moment applied to the cylinder by the bonded area and mean radius of the cylinder. (17) For the particular cylinders used in this experiment, the maximum shear stress on the outer surface of the joint is eight percent greater than the average shear stress as computed above. (18) This variation in stress could be considered when testing the ultimate strength of a brittle adhesive in this apparatus. This variation in stress becomes smaller as the radius of the cylinder is increased and the thickness of the wall is decreased. The significance of the variation in stress is also reduced if the adhesive to be tested is not brittle but one that will flow at the outer, highly stressed

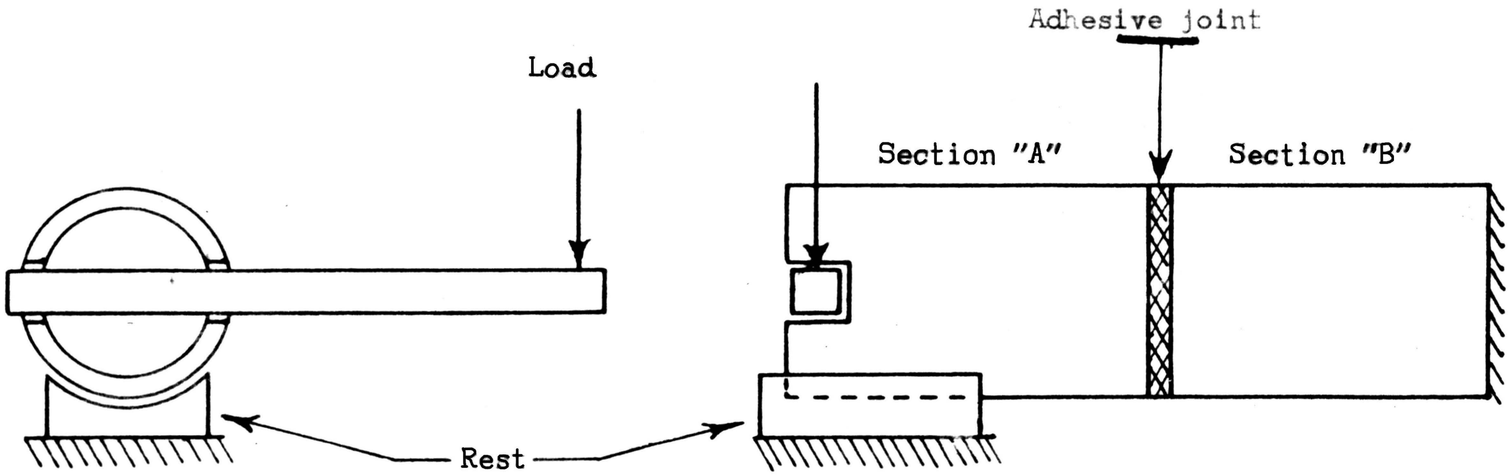



Figure 6 Schematic diagram of a torsion-shear apparatus

areas.

Since in this experiment the absolute values of stress are of secondary importance, the stress was assumed to be constant throughout the joint and the average stress recorded as being the true stress in the joint for all adhesive materials.

## THE BEHAVIOR OF MATERIALS AS A FUNCTION OF RATE OF LOADING

### Perfectly elastic materials:

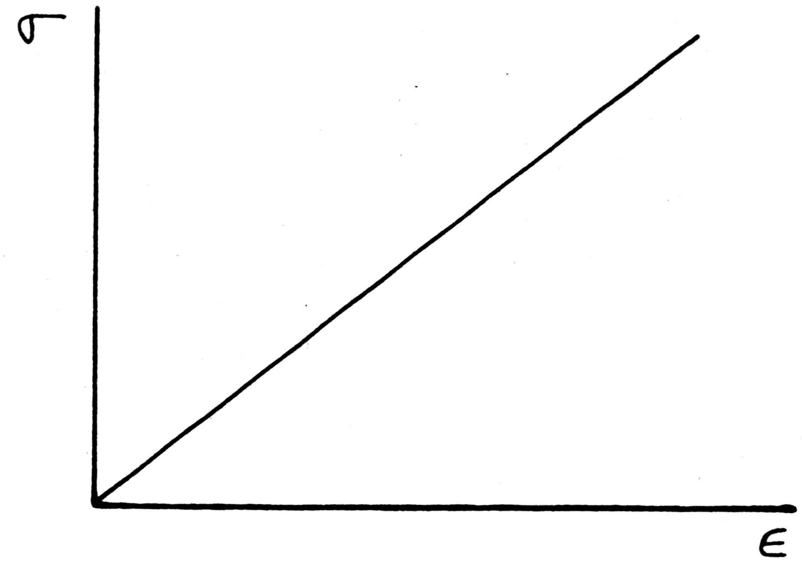
Most solid materials exhibit a certain amount of elasticity. If a body is perfectly elastic, a deformation caused by an externally applied force will disappear if the force is removed. The perfectly elastic solid will retain no memory of how or when the forces were applied so long as none of the forces were great enough to cause rupture. Any external force information is transmitted to all parts of the solid. Consequently, a perfectly elastic solid would not be sensitive to the rate of loading. The stress-strain relationship for a particular material would appear as shown in Figure 7(a) for any rate of loading.

### Perfectly plastic materials:

A perfectly plastic material has been defined as a material that behaves elastically until the stress reaches a certain critical value $\sigma'$; after which the material flows plastically under the constant stress $\sigma'$. A stress-strain diagram for a perfectly plastic material is shown in Figure 7(b). Section OA of the curve represents the elastic portion of the deformation while section AD represents the plastic flow as deformation continues at $\sigma'$. The perfectly plastic material exhibits no viscosity effects during the flow. Therefore, the perfectly plastic material would not be sensitive to changes in rate of loading and the stress-strain relationship for a particular material would always remain the same.

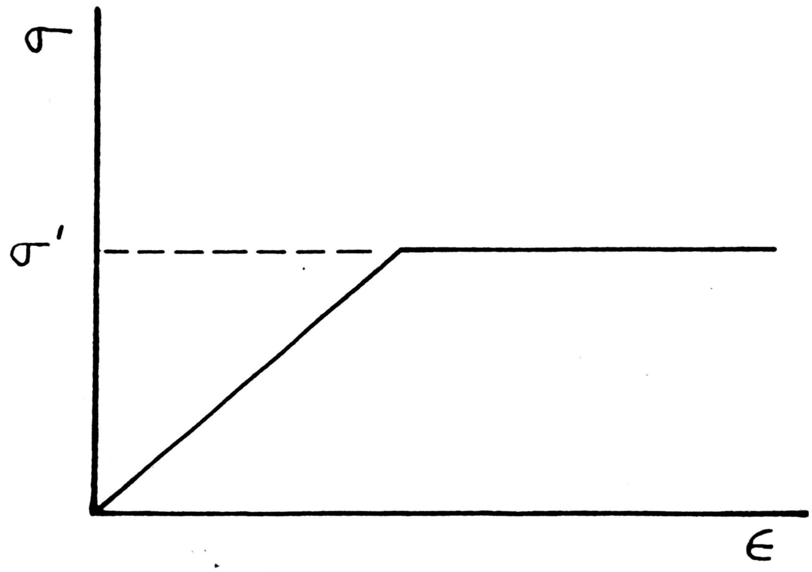
### Viscous fluids:

In a viscous fluid, the shearing or friction stress developed




Perfectly elastic material

(a)

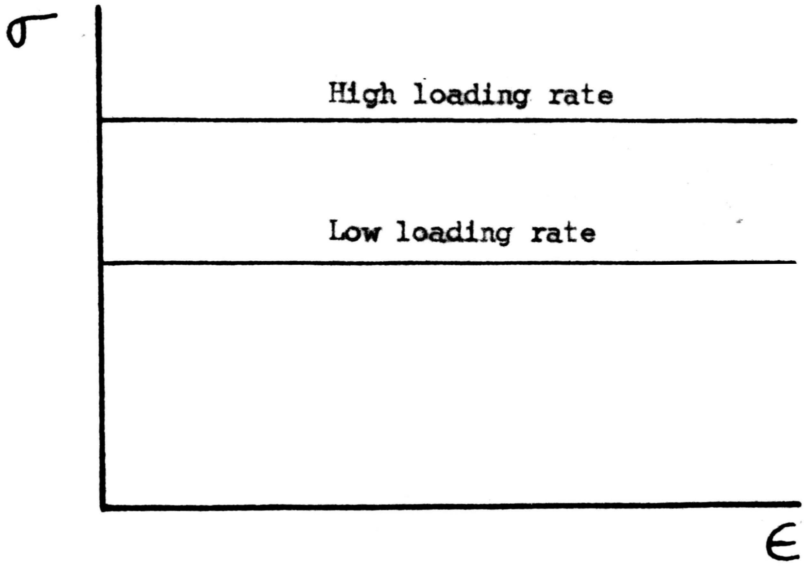



Perfectly plastic material

(b)

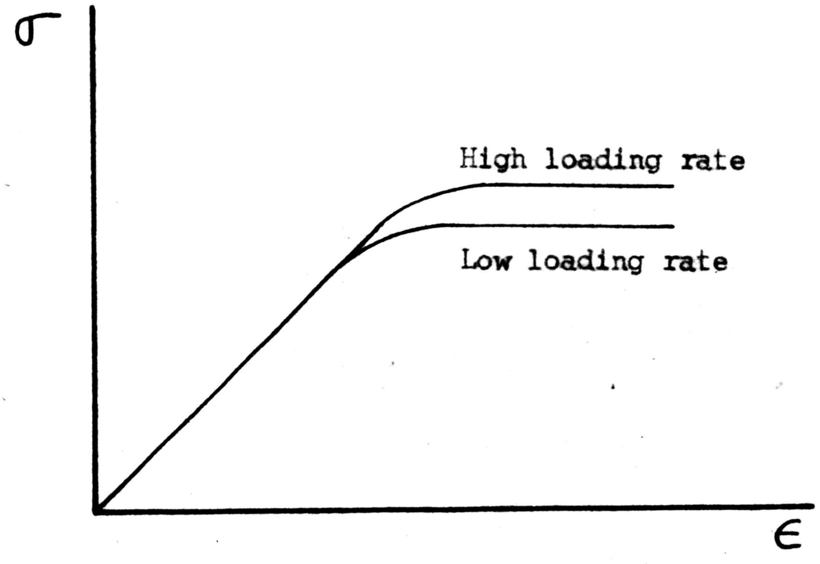
Figure 7 Stress-strain diagrams, any loading rate between the fluid layers is proportional to the rate of deformation and the viscosity of the fluid. For a fluid with a fixed viscosity, as the velocity of deformation is increased, the resistance to deformation increases. For this reason, a material whose characteristics are rate sensitive is said to exhibit viscous properties. Figure 8(a) illustrates the stress-strain relationship for a viscous material at two different rates of deformation.

Real materials can exhibit both elastic and viscous reaction to deformations. For example, steel is elastic for small strains of short duration, but will flow under large strains of short duration (yield) and small strains of long duration (creep). The apparent stress necessary to continuously deform steel above the yield point is a function of the rate of loading and increases as the rate of loading increases. The ultimate stress of copper and aluminum shows a similar dependence on rate of loading. (19) This effect becomes more pronounced as the temperature of the material is increased. These materials may be said to exhibit viscous effects since they are sensitive to the rate of loading. Figure 8(b) illustrates the effects of loading rate on the stress-strain relationship for a material with negligible strain hardening.




Viscous fluid

(a)




A material that is viscous in the plastic region

(b)

Figure 8 Stress-strain diagrams

## INTRODUCTION TO DISCUSSION OF TORSION-SHEAR APPARATUS

The ability of the torsion-shear loading apparatus to detect the stress-strain characteristics of an adhesive material at various rates of loading is discussed in this section. Figure 6 showing the torsion-shear apparatus is repeated on the following page.

No instruments for measuring the strain in the joint were available. Due to the small physical dimensions of an adhesive joint, the amount of deformation is small and, therefore, difficult to detect. Instruments for recording stress as a function of time were available. If the lever arm is deformed at a constant rate and the stress in the apparatus is recorded versus a constant time base, the resulting curve will be the stress-strain curve for the complete apparatus.

The significance of these stress-time curves is discussed in the following section. Several hypothetical adhesive materials of different stress-strain characteristics are used to join the cylindrical sections A and B and examples of the resulting stress-time or stress-strain curves are examined. In this analysis, the lever arm, the cylindrical sections A and B and the connections between these components are assumed to be perfectly elastic throughout the range of loading considered. The cylinder is assumed to be loaded in pure torsion and axial loads are assumed to be non-existant.

## ANALYSIS OF TORSION-SHEAR APPARATUS

### A-B IS A CONTINUOUS SECTION OF TUBING

If A and B are not joined with an adhesive, but are a continuous section of perfectly elastic tubing, a constant velocity of deformation will yield a constant rate of increase in stress at any point in the

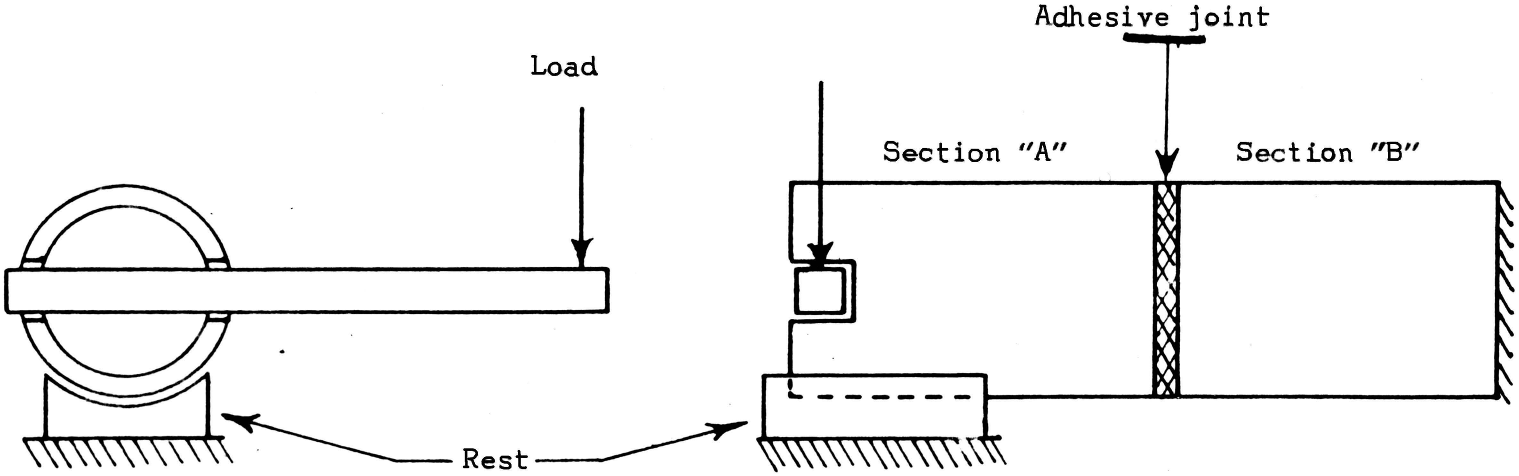



Figure 6 Schematic diagram of a torsion-shear apparatus (Repeated)

apparatus. A curve showing stress as a function of time for this case is represented in Figure 9. The slope of this curve can be thought of as representing the apparent modulus of the apparatus. If A and B are joined with an adhesive material with the same elastic modulus as A and B, the stress-time relationship will be the same as that for a continuous specimen.

A-B JOINED WITH PERFECTLY ELASTIC ADHESIVE WITH MODULUS DIFFERING FROM MODULUS AND A AND B

If a small section of A-B is replaced with an adhesive material with a modulus differing from the modulus of A-B, the same constant velocity of deformation will yield a constant rate of increase in stress at any point in the apparatus. The rate of increase of stress, (the slope of the stress-time curve) will differ from the stress rate of a continuous section. The amount and direction of this variation would depend upon the value of the modulus of the adhesive material and the length of section replaced with adhesive material (joint thickness). For the same velocity of deformation, the same time base and the same joint thickness, the substitution of a high modulus adhesive will result in a steeper slope and a lower modulus, a lower slope. The apparent modulus of the apparatus increases or decreases as the modulus of part of the apparatus increases or decreases.

In an actual test, the adhesive joint represents only about one-tenth of one percent of the total length of the specimen A-B. Elastic joint deformation represents even a smaller percentage of the total deformation of the apparatus. Adhesives used in this experiment have values of moduli of about .3 x $10^6$ psi (taken from manufacturers specification sheet). The presence of a 0.010 inch thick, elastic,

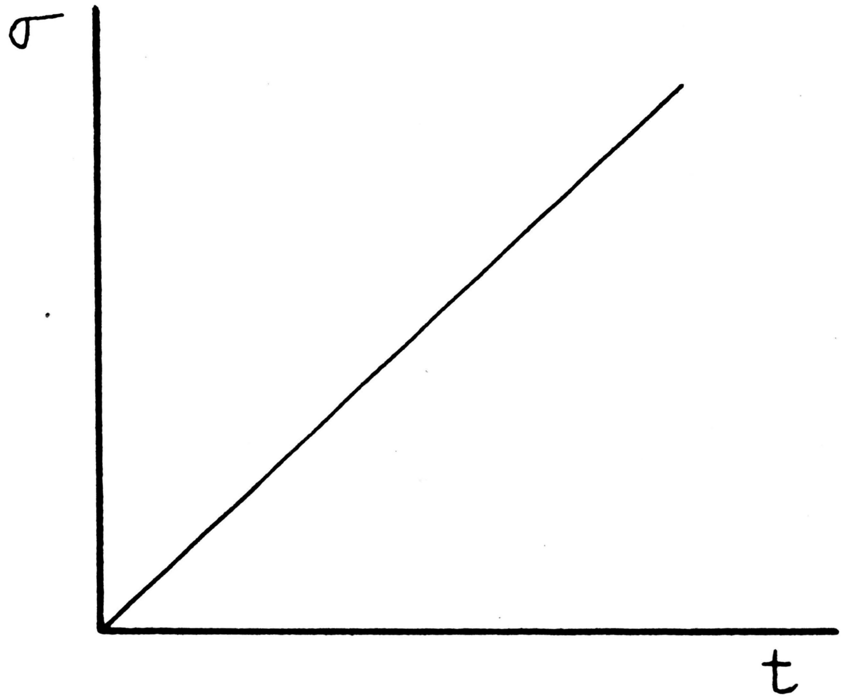



Figure 9 Stress-time relationship for a continuous elastic specimen, any rate of loading

adhesive joint of such a material would have the effect of decreasing the apparent modulus of the apparatus about four percent. It would be difficult to experimentally detect the effects of varying adhesive moduli upon stress rate for adhesive moduli equal to, greater than, or slightly less than the modulus of the section A-B with this apparatus. Only the stress at rupture can be determined from the curve.

The curve shown in Figure 10 illustrates the effects of high and low modulus, elastic adhesives upon the slope of the stress-time curve. These effects are exaggerated for the purpose of demonstration.

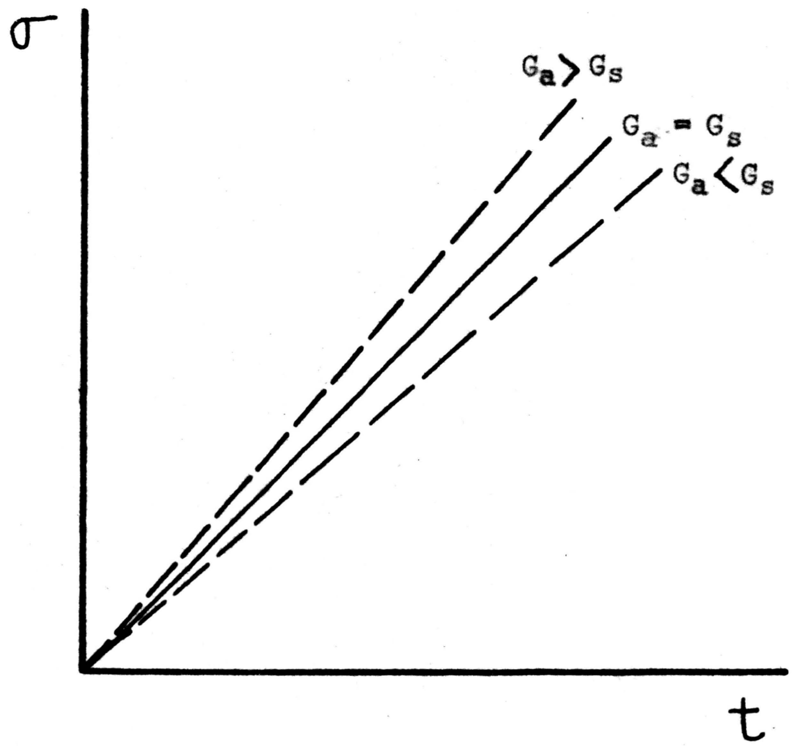
A-B JOINED WITH A PERFECTLY PLASTIC ADHESIVE

If A and B are joined with a perfectly plastic adhesive material whose yield stress is less than the yield stress of any part of the loading apparatus, the stress-time curve will indicate a constant increase in stress with time until the yield stress in shear of the adhesive is reached, after which, the stress will remain constant as the adhesive flows. The apparatus is, therefore, capable of detecting the stress at which the adhesive flows. Figure 11 shows the curve of stress as a function of time that would be obtained from the apparatus when A and B are joined with a perfectly plastic adhesive.

A-B JOINED WITH A VISCOUS ADHESIVE

If A and B are joined with a viscous adhesive material, the stress-time curve would reveal the characteristics of the flow process as a function of time. Figure 12 shows the stress time relationship for adhesive material that is elastic for small deformations and viscous in the plastic region. This curve is representative of many real materials.

It may be concluded that the torsion-shear apparatus containing




$G_a$ = Elastic modulus of adhesive

$G_s$ = Elastic modulus of specimen A—B

Figure 10 Stress-time relationship for a specimen (A—B) bonded with an elastic adhesive, any loading rate

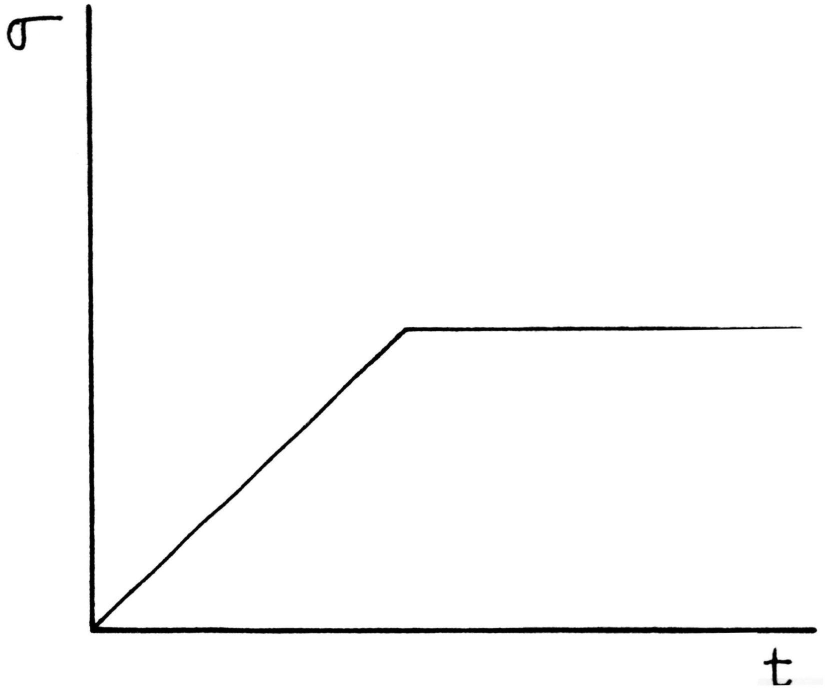



Figure 11 Stress-time relationship for a perfectly plastic adhesive, any rate of loading

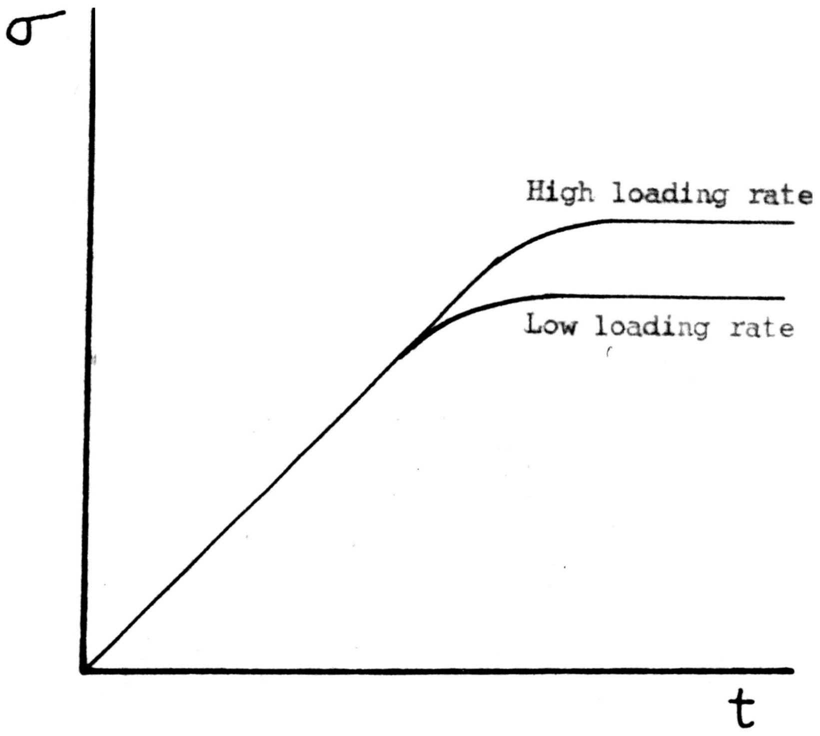



Figure 12 Stress-time relationship for a material that is viscous in the plastic region.

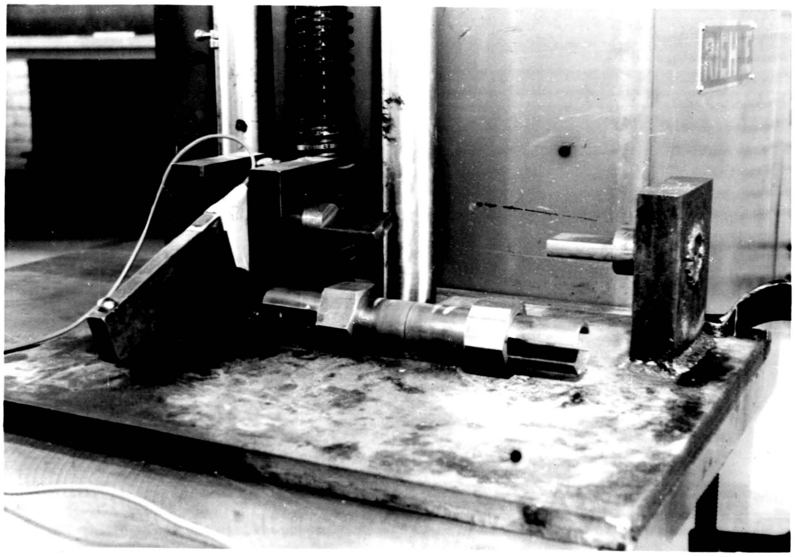
a bonded specimen and instrumented to measure stress versus time is capable of detecting the magnitude of the rupture stress for an elastic adhesive material and the existance, magnitude and characteristics of the flow process for a plastic or viscous adhesive material. Since a material must exhibit viscous flow characteristics to be sensitive to rate of loading, this apparatus will provide the necessary information to study the effects of rate of loading on adhesive joint strength. The assumptions concerning the apparatus made in the introduction to this section will be qualified in the following discussion.

## CONSTRUCTION AND CALIBRATION OF LOADING APPARATUS

The torsion-shear apparatus built for this test and a test specimen are shown in Figure 13. The apparatus was designed so that a conventional testing machine could be used to load the lever arm causing an axial torque in the tube.

A test specimen consists of two, thin walled cylinders, each five inches in length and slotted on one end. These two cylinders are bonded together on their smooth ends and the assembled specimen is fitted into the torsion loading apparatus. The hexagonal sleeves on each end of the specimen are used to center the specimen in the loading apparatus and to discourage buckeling of the ends of the tube at high loads. A more detailed discussion of the preparation of the test specimens is included in a separate section.

A test was run for the purpose of evaluating any longitudinal bending moment or axial load in the test specimen. A continuous section of tubing made of the same stock as was used for the test specimens was machined to specimen dimensions. Two SR-4 strain gages were cemented parallel to the axis of the tube at the longitudinal center and 90 degrees apart. This specimen is shown in the loading apparatus in Figure 14. The apparatus was loaded by the testing machine through the range of loads used in an actual test. Readings of strain on the surface of the specimen as indicated by the two longitudinal gages were recorded at several intermediate loads using a Baldwin SR-4 Strain Indicator. The stress on the surface was then calculated from these measurements. The results of this test are shown graphically in Figure 15, where stress at each gage is plotted against the torsion in the specimen.



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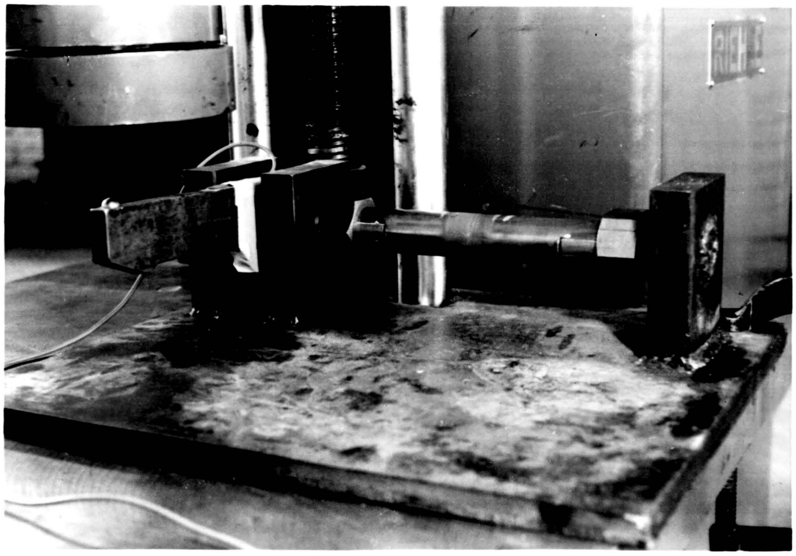

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Figure 13 The torsion--shear apparatus used in this experiment with a specimen.

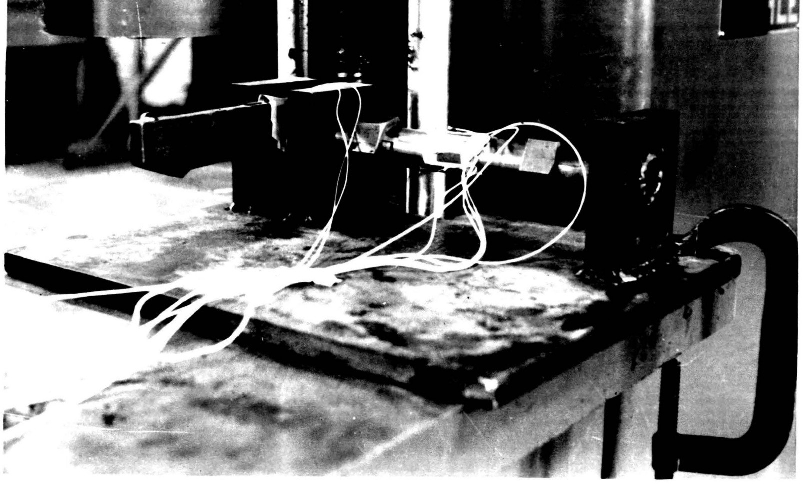

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Figure 14 The torsion-shear apparatus loaded with the continuous calibration specimen.

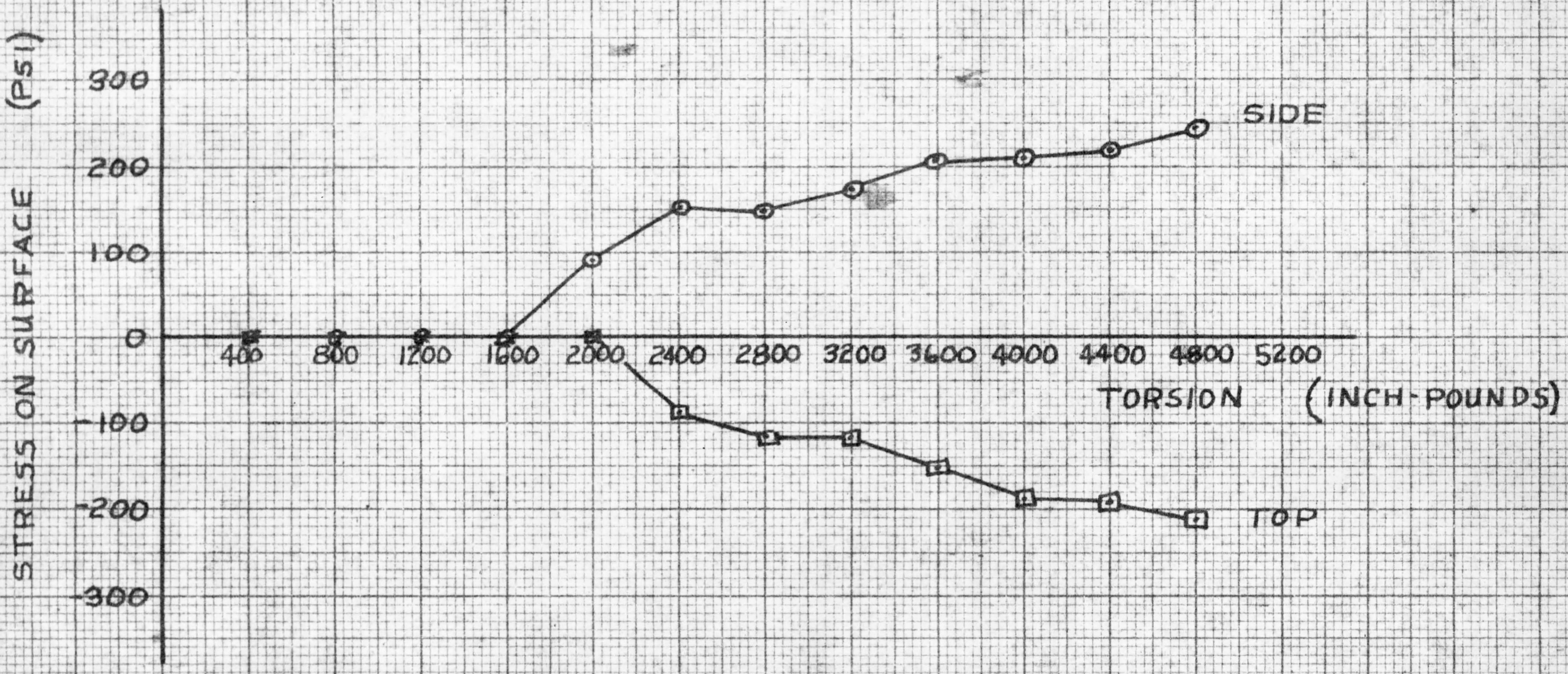


FIGURE 15 STRESS IN SPECIMEN DUE TO BENDING

For the adhesives tested in this experiment, the stress due to axial load and longitudinal bending was always less than three percent of the stress due to torsion in the section. Because of their relatively small magnitude, the effects of bending and axial stress upon the apparent shear stress in the adhesive joint were not considered.

The load in the apparatus was sensed by measuring the strain on the top of the torque arm with a SR-4 strain gage. This strain was calibrated to the torque in the test specimen; consequently, it was not necessary to attach strain gages to every test specimen. A strain gage was attached to a continuous section of tubing at an angle of forty-five degrees. The apparatus was loaded through the usable range of loads and readings of strain on the arm and strain on the forty-five degree gage on the specimen were recorded at several intervals of load. Strain on the arm versus strain on the specimen is plotted in Figure 16. The linear relationship between these two strains indicates that the arm, the specimen and the connections between these elements behave in an elastic manner, thereby qualifying the technique of sensing load in the specimen indirectly.

The calibration specimen and the strain indicating equipment are shown in place in Figure 17.

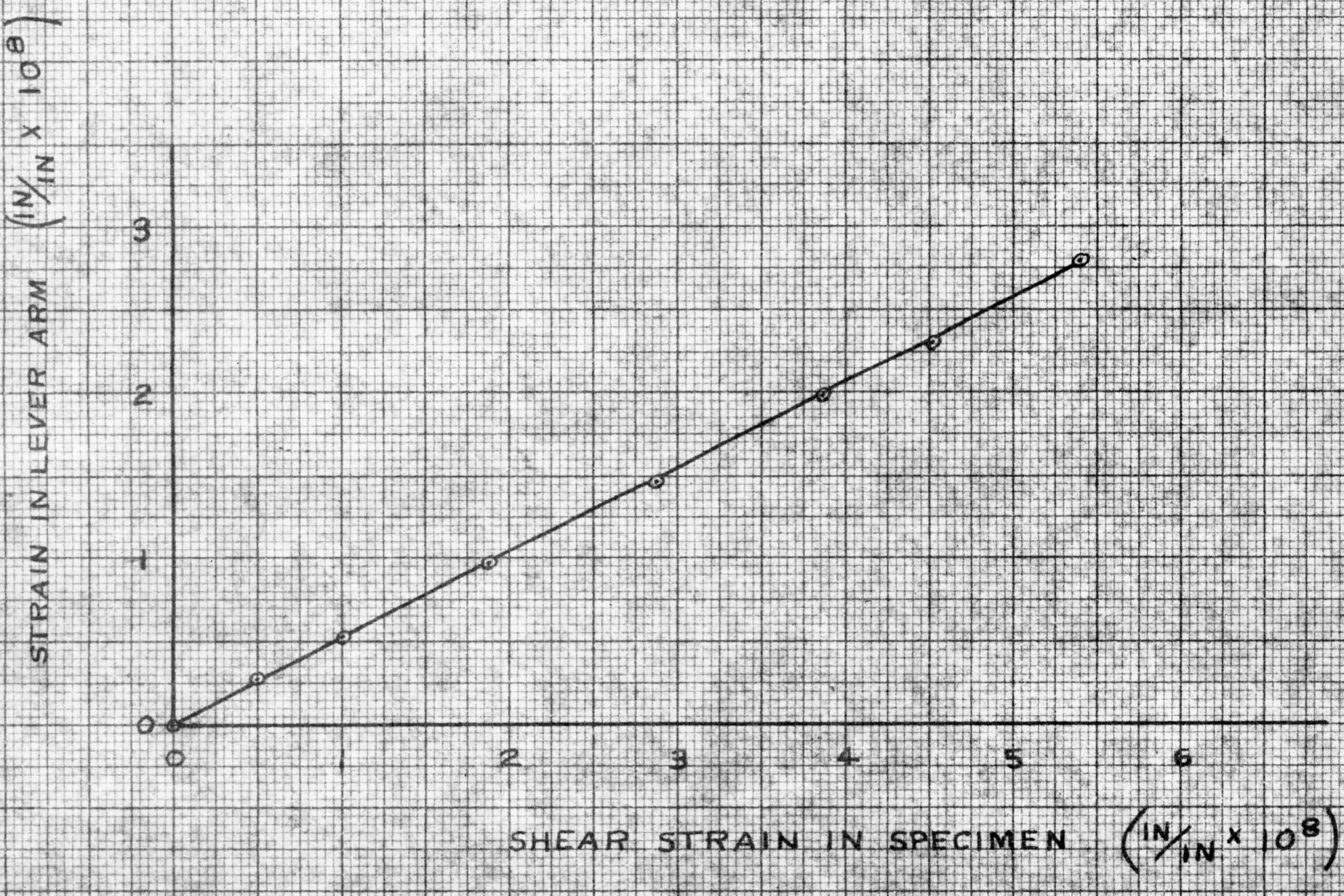


FIGURE 16 CALIBRATION CURVE

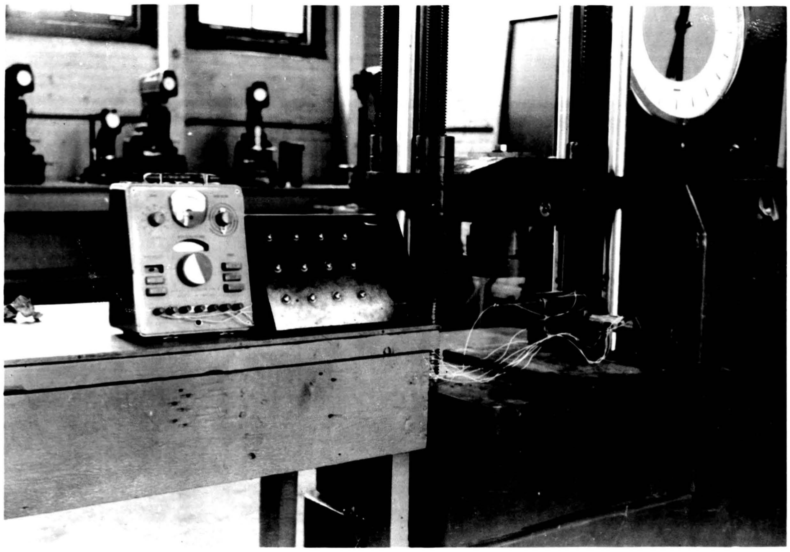

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Figure 17 The calibration specimen and strain indicating equipment in place.

PREPARATION OF SPECIMENS

The specimens were machined from 1 7-16 inch outside diameter tubular steel stock. Two parts, each five inches in length, were slotted for two inches along the longitudinal axis on one end and faced perpendicular to the longitudinal axis on the other end. Perpendicularity of the faced ends was held to within plus or minus 0.001 inch. These two parts, bonded together on the faced ends constituted a specimen. A total of twenty specimens were machined for this test. All specimens were stamped with a number to enable one to relate a consistantly poor test result to a specimen peculiarity.

The adhesives used in this test were shipped from the factory less than two months before their use. It was assumed that the adhesive had not aged enough to significantly effect its strength properties. The types of adhesives used in this test have a shelf life of at least one year. The adhesives were stored in sealed containers so that chemical contamination was kept at a minimum.

Nearly all of the structural, metal-to-metal adhesives are two component adhesives and must be thoroughly mixed right before they are used. The manufacturer recommends that mixing tolerances of plus or minus five percent be maintained. In this experiment, mixing tolerances of less than plus or minus three percent were maintained.

All of the test specimens using a particular adhesive were assembled at the same time using the same batch of adhesive thereby minimizing possible mixing and ageing variables.

Careful preparation of the surfaces to be bonded is necessary to promote good adhesion. The specimens were mechanically cleaned with a wire brush and emery paper, degreased in solvent and etched for thirty minutes in a solution of twenty parts nitric acid and two parts hydroflouric acid in water. The specimens were then washed with water and allowed to dry. The apparatus pictured in Figure 18 was used to suspend the specimens in the etching solution. All twenty specimens could be etched simultaneously with this apparatus.

The edge geometry of the adhesive joint was controlled by fitting a single layer of paper around the inside of the tube as shown in Figure 19. Any surplus adhesive on the outside of the joint was removed with a file after the adhesive had been cured. Examination of the broken specimens showed that the inside surface of the joint was flush with the inside of the tube. Each specimen rested in a V-block as it was cured, Figure 19. A layer of aluminum foil was placed between the specimen and the V-block to prevent adhesion of the specimen to the V-block.

The thickness of the adhesive in the joint will sometimes effect the apparent strength of the joint. This effect is more noticable when testing the tensile strength of an adhesive. Very thin joints will tend to resist higher tensile stress than thick joints.

When a fluid or a plastic adhesive, i.e., one that will not withstand large shear stress, is spread in a very thin layer between two rigid, plane surfaces, lateral contraction is prevented and the material must fail in tension. This apparent tensile stress is much higher than the tensile stress observed with a thick layer of material since when the layer is thick the material can fail in shear. For brittle materials, the higher strength of thin glue lines may be partially attributed to the fact that the probability of having a flaw is reduced as the thickness on the layer is reduced. (20)

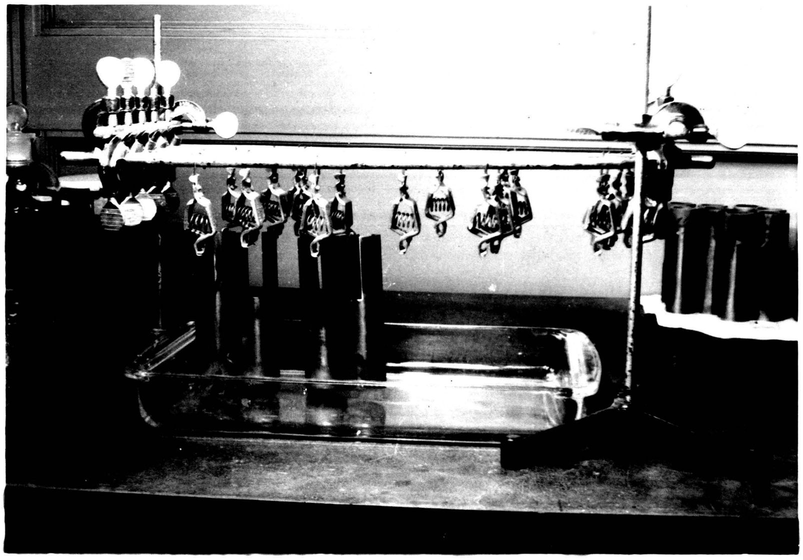

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Figure 18 Etching apparatus

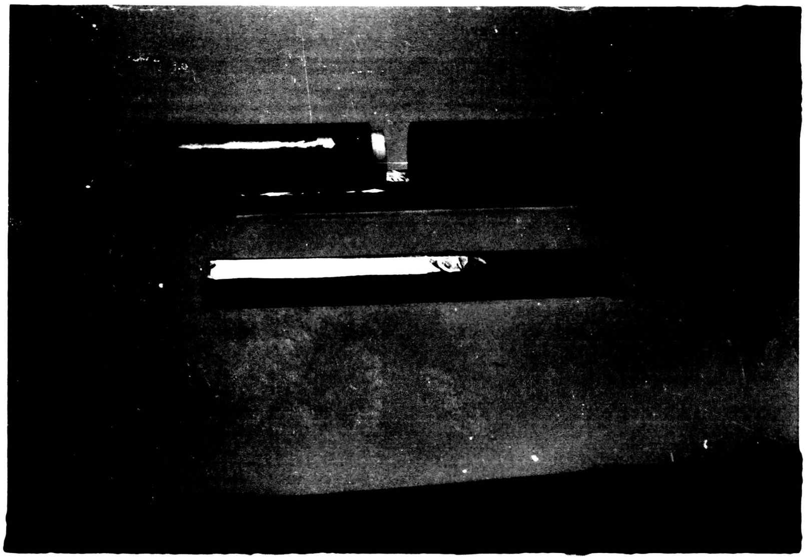

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Figure 19 A test specimen resting in a V-block before being bonded. Note the paper liner in the left half of the specimen.

Bonded lap joint tests show little variation in strength for joint thicknesses between .001 and .015 inches. (21) The author has conducted a shear block test in which the glue joint thickness was varied between .003 and .065 inches. No significant changes in apparent shear-stress could be noted over this range.

For this experiment, a special jig was built to accurately adjust the thickness of the glue line by measuring the initial and final length of the specimen. A picture of this jig is shown in Figure 20. The adjustable end of the jig consisted of a disc fastened to one end of a threaded shaft. This shaft was screwed through the fixed upright on the left end of the base. A ball-point fixture was attached to the opposite end of the threaded shaft and could be seated firmly against the end of the specimen. Rotation of the disc was permanently calibrated to the axial movement of the threaded shaft. The device had a readability of plus or minus 0.00005 inches and a reproducibility of at least plus or minus 0.001 inches.

A specimen was prepared as follows:

(1) A dry specimen was placed on a V-block and fitted into the measuring jig.

(2) The movable end was secured against the end of the specimen and a reading of the initial length of the specimen was taken from the calibrated disc. The movable end was then unscrewed to release the specimen.

(3) The specimen was removed from the jig and the adhesive was spread on both faces of the tubes. The tubes were replaced in the V-block and this assembly was again placed in the measuring jig.

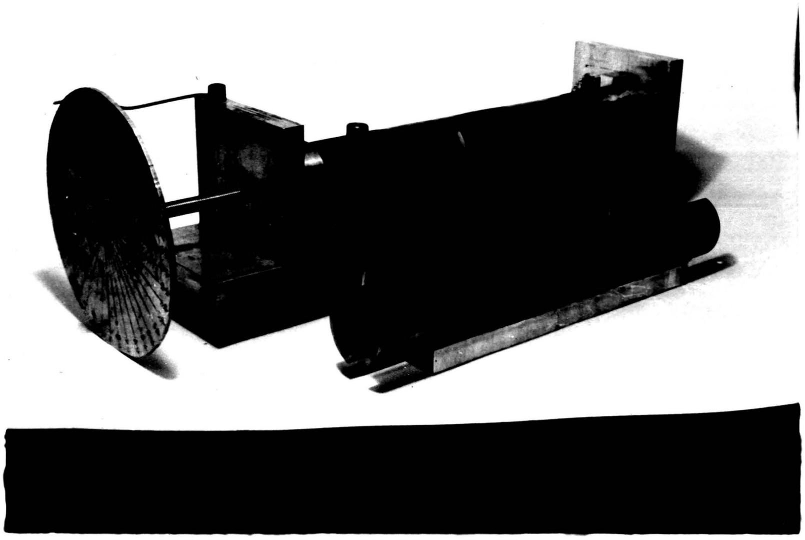

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Figure 20 The measuring jig used to adjust the glue line thickness.

(4) The movable end was then screwed in until the calibrated disc indicated the desired final reading. The width of the glue line was equal to the difference between the initial and final readings on the calibrated disc.

After the glue line thickness had been adjusted, the specimen was removed from the jig and placed in an oven to cure. The measuring jig also served the purpose of aligning the slotted ends of the two pieces of the specimen so that they would fit into the loading apparatus.

Most metal-to-metal adhesives must be cured at temperatures of 200-300°F for a period of one to two hours. The manufacturer of the adhesive specifies the time and temperature necessary to cure his adhesive. The adhesives used in this experiment were cured in accordance with the manufacturers recommendations.

The oven used to cure the specimens is shown in Figure 21. During the curing process, the temperature of each shelf of specimens was frequently monitored. The shelves could be shifted to various positions in the oven to maintain nearly uniform cure temperatures for each specimen.


Figure 21  Specimens curing in oven.

## INSTRUMENTATION OF LOADING APPARATUS

A Brush, Model BL-520 Amplifier and a Model BL-201 Direct Writing Oscillograph were used to record stress in the apparatus versus time as the apparatus was deformed at a uniform rate. A Wheatstone bridge is incorporated into this instrument so that a strain gage may be wired directly to the instrument. The calibrated strain gage located on the top of the loading arm was used to sense strain in the loading apparatus. The complete testing apparatus is shown in Figure 22.

The instruments were calibrated for each test in accordance with the calibration procedure outlined in the operating manual.

A reproduction of a stress-time curve obtained from loading a continuous specimen with a constant head velocity is shown in Figure 23. The non-linear portion of the lower part of the curve is due to slack in the apparatus. The curve is linear in the region of higher stresses, indicating that the apparatus was behaving elastically and was being loaded at a uniform rate. All adhesive joint failures occurred at stresses well within the linear portion of the stress-time curve.

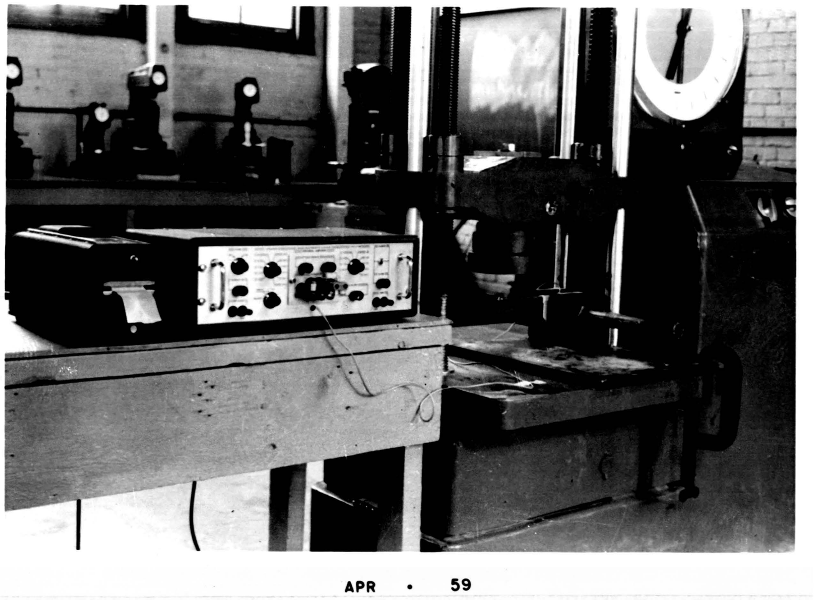



Figure 22 Testing apparatus, shown complete with instrumentation used in place.

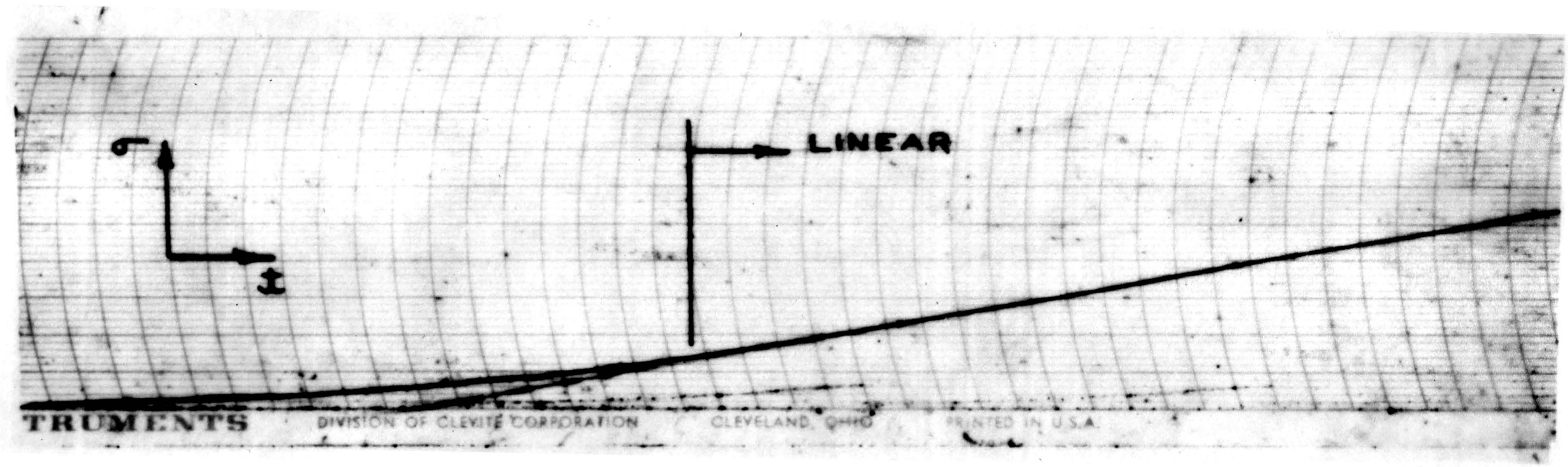



Figure 23 Stress-time curve for continuous specimen. Note that the curve is linear for higher stresses.

## THE TEST

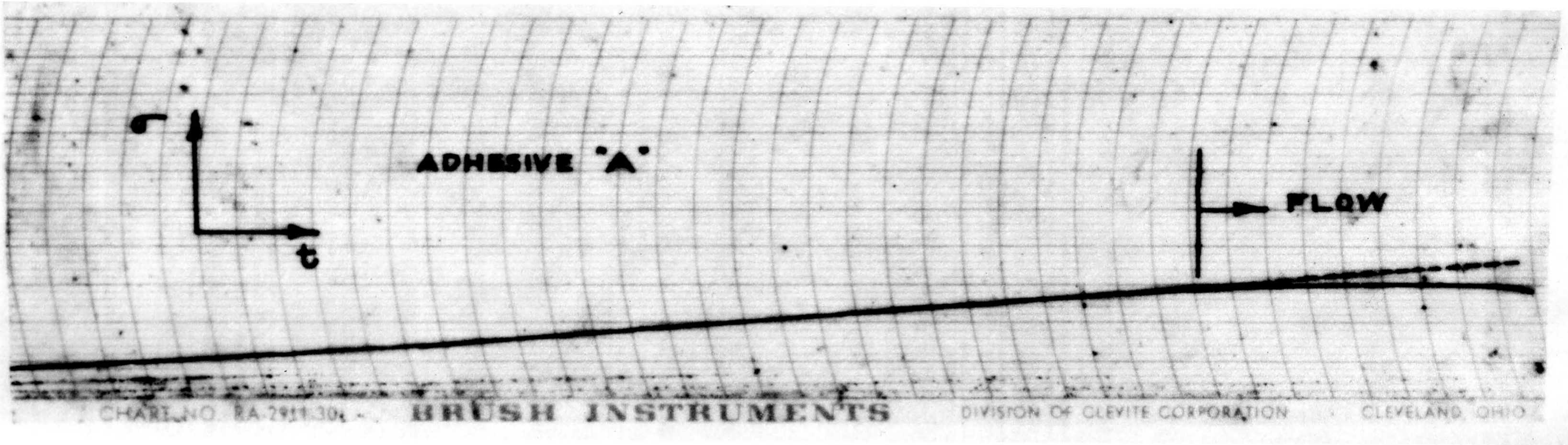
A total of six different adhesives were tested for their sensitivity to rate of loading. The adhesives tested were representative of the types of adhesives used in industry for metal-to-metal bonding at the present time. Two of these six adhesives had been designed for special industrial applications and did not adhere satisfactorily to the test specimens. The data taken using these two adhesives were judged to be inconclusive and are, therefore, not presented.

Each adhesive was used to prepare twenty specimens. These specimens were then divided into four groups and each group was tested at a different rate of loading. The rates of loading are referred to the loading head velocity of the testing machine. The testing machine used was equipped with an automatic control system to maintain uniform head velocity. Head velocities of 0.25, 1, 5, and 20 inches per minute were used. A head velocity of one inch per minute loaded the specimen at a rate of approximately 34,000 pounds per square inch per minute.

The ultimate shear strength of all the adhesives tested showed some dependence on the rate of loading. As the rate of loading was increased, the ultimate shear strength increased. The adhesives are given the code names of A, B, C, and D for purposes of this discussion.

The ultimate shear strength of adhesives A and B exhibited a definite dependence upon rate of loading. The stress-time curves for these materials showed a distinct yielding at a stress, which was nearly constant for all rates of loading. Typical examples of the stress-time curves for adhesives A and B are shown in Figure 24.

The average deviation from the mean for a particular run was on the order of 200 psi. This is a relatively low deviation for an



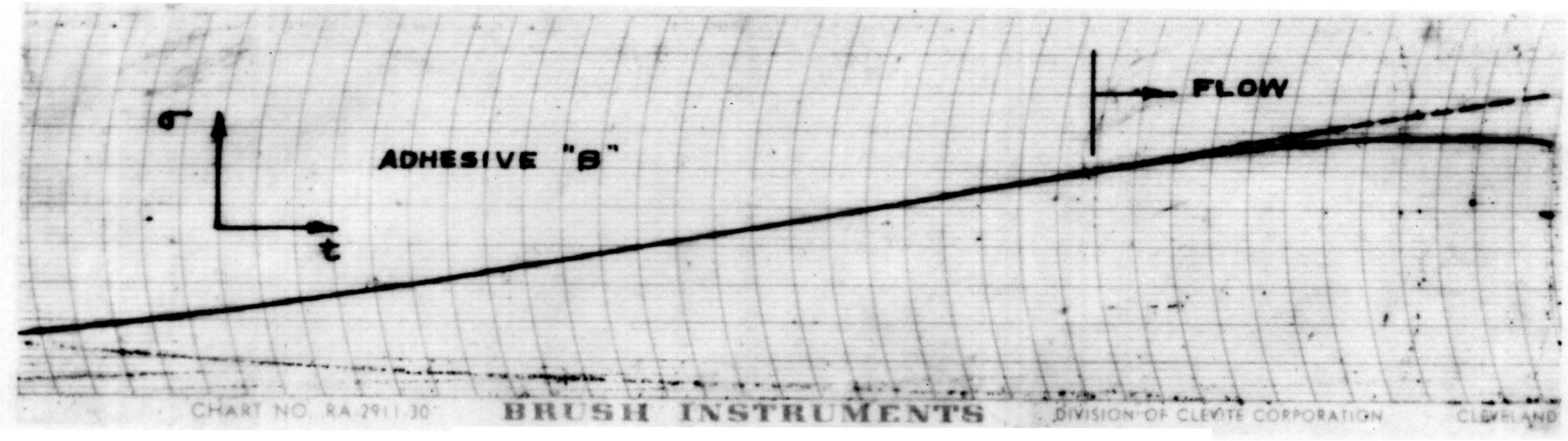




Figure 24 Typical stress-time curves for adhesives A and B. A dashed line has been used to extend the elastic portion of the curve to illustrate where the flow began.

adhesive joint test. Since A and B exhibited ductile characteristics, it may be assumed that the stress concentrations in the joint were relieved thereby distributing the load more uniformly throughout the joint. This could offer an explanation of the low deviation.

Ultimate stress is plotted against loading rate for adhesives A and B in Figures 25 and 26. All data points have been plotted to demonstrate the scatter. The trend has been approximated with a straight line representation.

Adhesives C and D were less dependent upon the rate of loading. The stress-time curves for these materials revealed that very little yielding was occurring, indicating a more brittle behavior. Typical examples of the stress-time curves for adhesives C and D are shown in Figure 27.

The average deviation from the mean for a particular run was on the order of 400 psi. The stress-time curves for adhesives C and D show that they are more brittle than adhesives A and B. Being more brittle, they would be more sensitive to possible stress concentrations in the joint and could be expected to show more deviation.

Ultimate stress is plotted against loading rate for adhesives C and D in Figures 28 and 29. All data points have been plotted to demonstrate the scatter.

It is difficult to determine a definite relationship between ultimate shear strength and loading rate from these data. A significant increase in ultimate shear strength with loading rate is indicated. A straight line has been drawn to indicate the probable relationship.

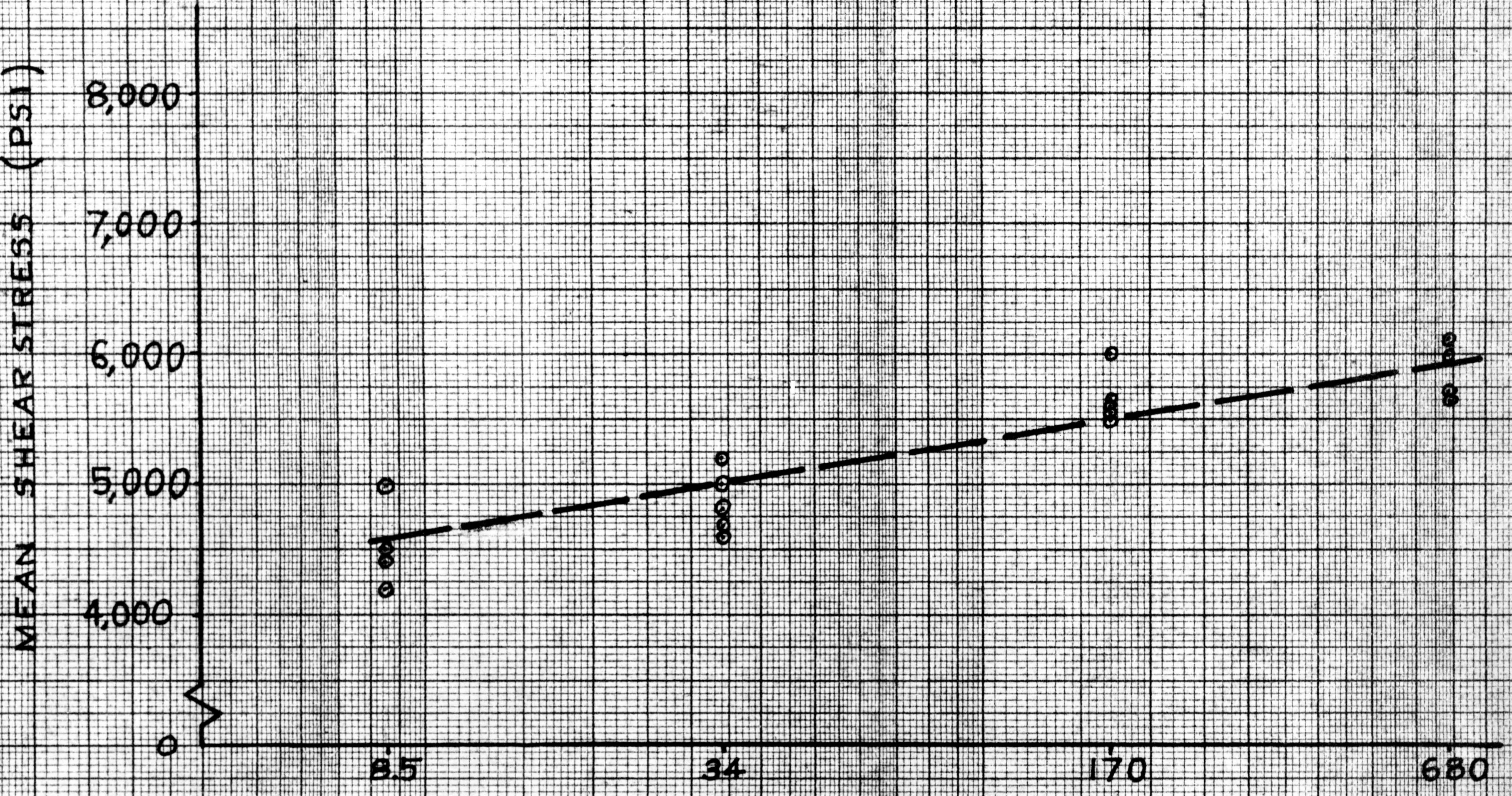



FIGURE 25 ULTIMATE SHEAR STRESS VS LOADING RATE

ADHESIVE A

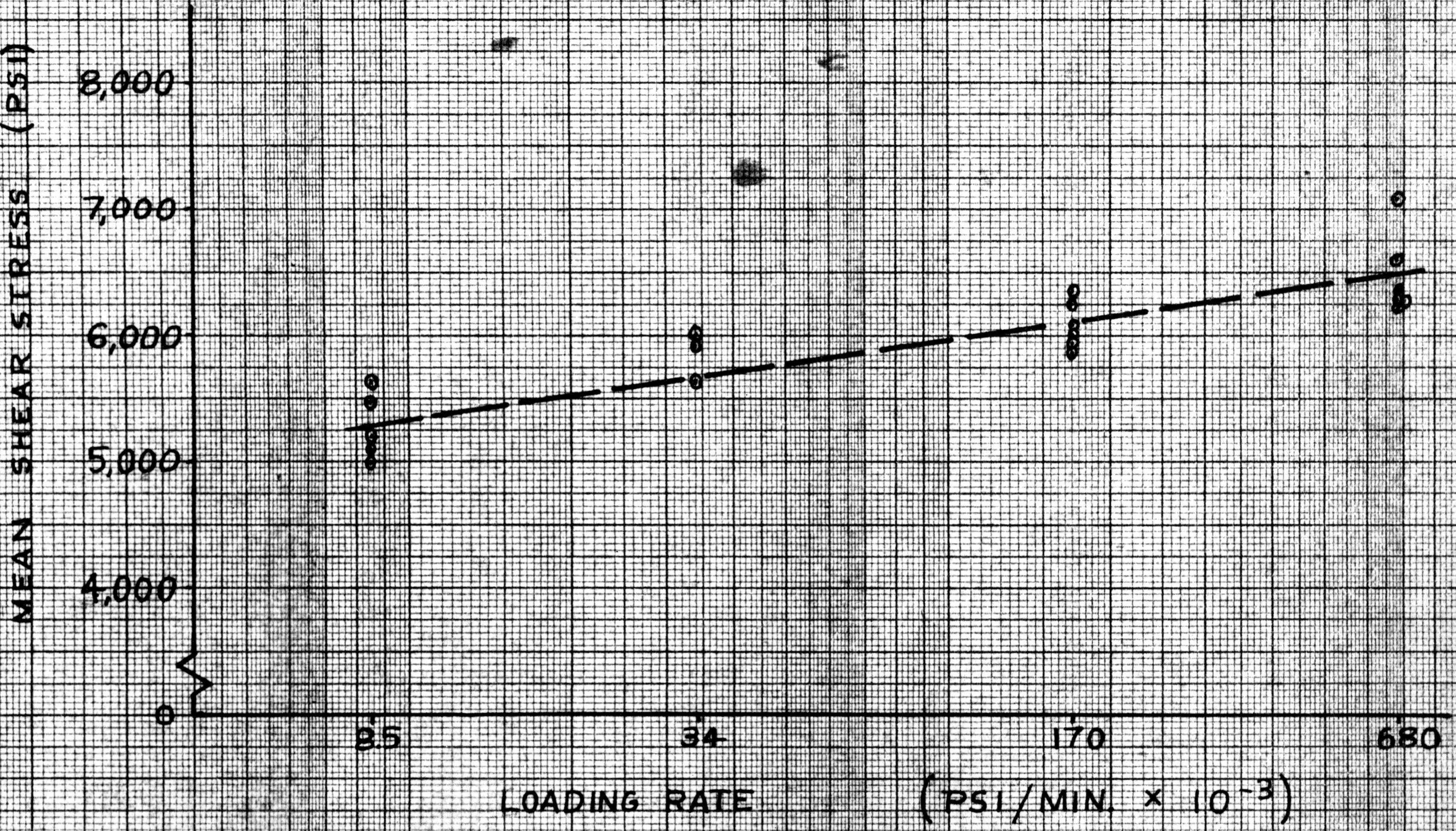



FIGURE 26 ULTIMATE SHEAR STRESS VS LOADING RATE

ADHESIVE B

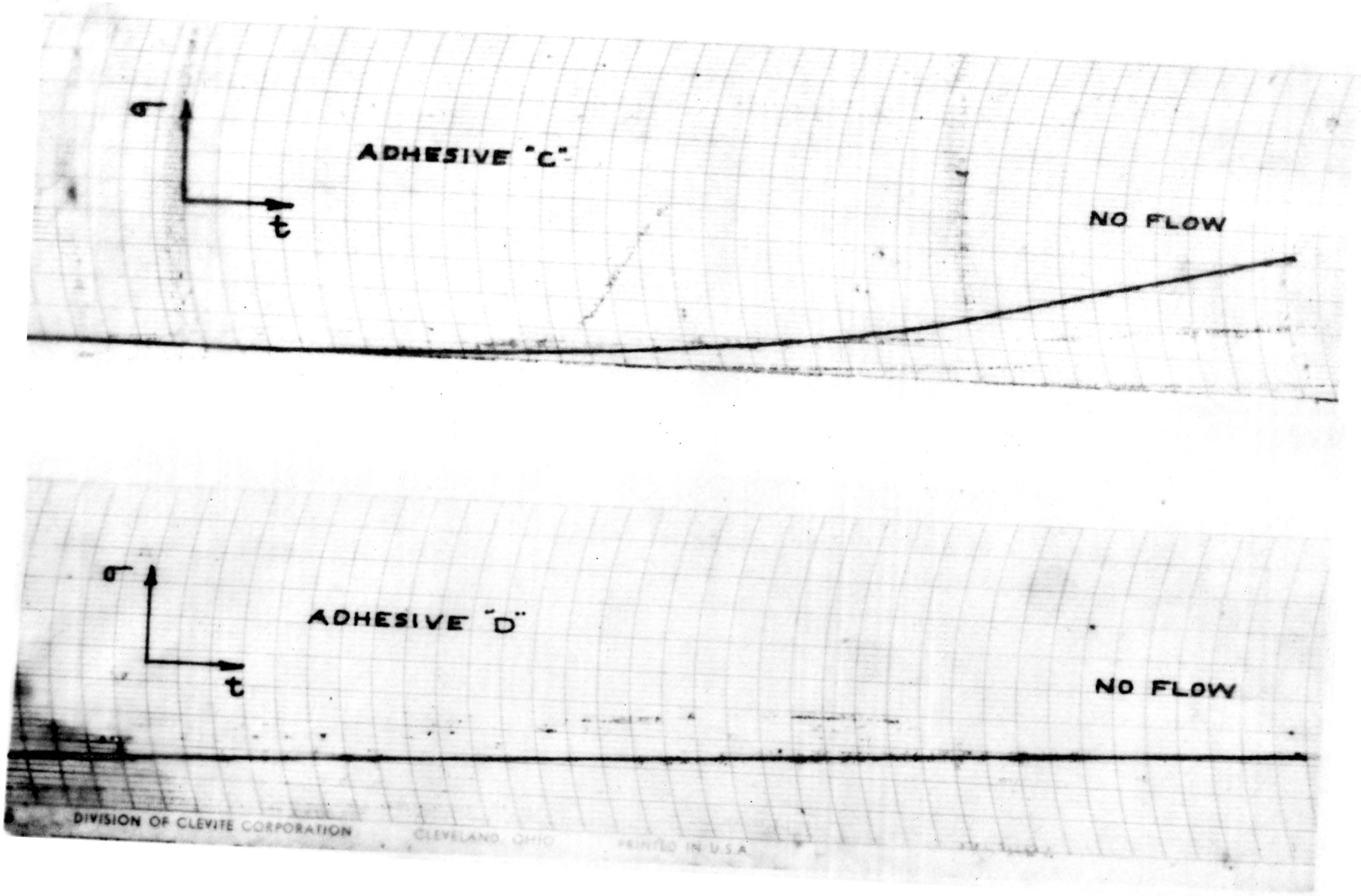



Figure 27 Typical stress-time curves for adhesives C and D. Note that no flow occurred before failure.

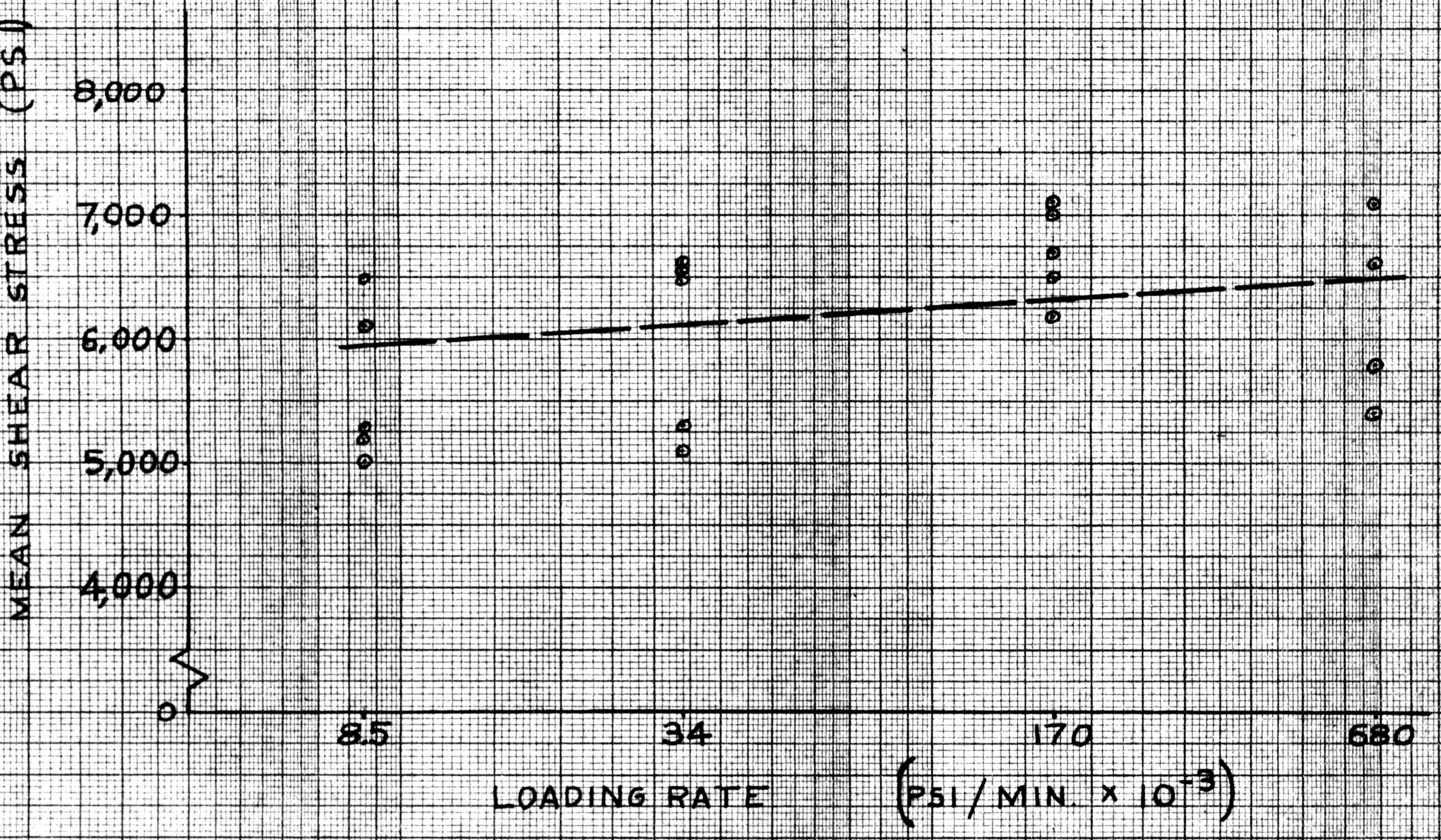



FIGURE 29 ULTIMATE SHEAR STRESS VS LOADING RATE

ADHESIVE D

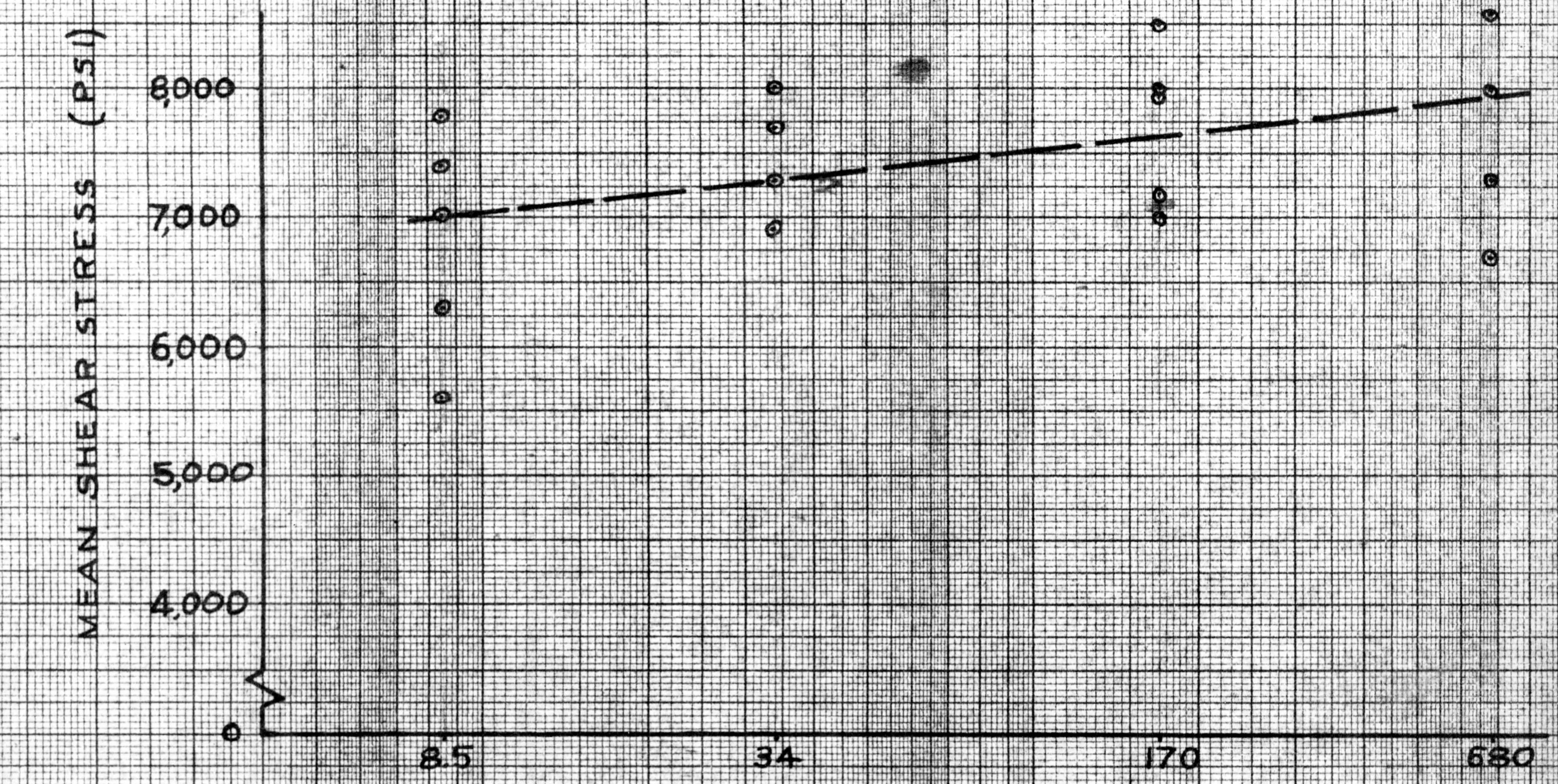



FIGURE 28 ULTIMATE SHEAR STRESS VS LOADING RATE

ADHESIVE C

CONCLUSIONS:

Rate of loading does effect the apparent shear strengths of the metal-to-metal adhesives tested in this experiment. The importance of the rate of loading variable cannot be correctly related to the modulus of a ductile adhesive material. Loading rate will effect the apparent joint strength only when the adhesive under consideration flows before rupturing. The stress-strain relationship for the adhesive will reveal any yielding or flow. Consequently, the stress-strain relationship provides a basis for judging possible rate of loading effects. As the amount of flow before rupture increases, the effect of loading rate upon ultimate joint strength becomes more pronounced.

The rate of loading used to test adhesive joint strengths should accompany the test results. The loading rates specified by the ASTM could provide the necessary standard of reference. If these standards are used, this information should be included in the test results.

The torsion shear test revealed higher shear strengths than those obtained by the manufacturer using the lap joint test. The apparent ultimate shear stresses determined in this test were often twice those obtained with the lap joint test. The torsion-shear technique, because of its lack of severe stress concentrations, could be used to provide useful shear strength data for adhesives.

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# VITA

Charless W. Fowlkes was born August 9, 1935, at Frumit, Missouri. He received elementary and three years of high school education in Jefferson County Missouri. The final year of high school was completed at Eureka, Missouri.

He enrolled at the Missouri School of Mines and Metallurgy in September of 1953, and received a Bachelor of Science Degree in Mechanical Engineering in June of 1957. In September, 1957, he was appointed an Instructor in Mechanical Engineering at the Missouri School of Mines and was enrolled as a graduate student in Mechanical Engineering.

During the summer of 1956, he was employed by Ethyl Corporation Research Laboratories in their Lubrication and Wear Department. During the summers of 1957 and 1958, he was employed by the Naval Ordnance Test Station in their Research and Weapons Development Departments.